Dependence of Aeration Efficiency in Projected Water Spray on Hydrodynamic Profile in a Water Treatment Tank

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Abstract— **In this study, measurements were conducted for the aeration efficiency and the oxygen transfer rate from the atmospheric air to water spray droplets in a water treatment tank to interpret the spray aerator characteristics. The applied measurement technique depended on the hydrodynamic flow profile inside the tank. The droplets were generated by the agitation due to the turbine rotation. The performed calculations were depending on a hydrodynamic profile database that was obtained by applying Particle Image Velocimetry (PIV). PIV apparatus has been used for the governed water flow by the tank internal configurations and geometry for a given turbine rotation speed. It was found that the oxygen mass transfer is controlled by flow pattern inside the tank. The generated water spray depends on the water flow redirected to the intake zone of the turbine. The calculated oxygen mass transfer and aeration efficiency that obtained by using PIV in the water droplets have a direct dependence on the way that the water flow pattern acts inside the tank.**

Keywords- water treatment, spray aeration, agitation, hydrodynamics, oxygen transfer rate

Introduction

Oxygen mass transfer in surface aerated tanks by spray projection mostly occurs at the water spray droplets surface and at the water surface. Then the operation of the oxygen transfer continues further inside the liquid body of the wastewater. So the oxygen transfer to the liquid has two ways; Firstly the direct to the liquid surface due to large eddies created at the surface by aerator rotation and, Secondly by contact of projected liquid droplets into the air and the oxygen transferred inside the liquid bulk by the entrained air bubbles [1].

Although the concept of dividing the mass transfer operation in the surface aeration process into two zones above and under water surface was identified in several previous works for the surface aeration and other types of aeration [2, 3]. But generally the oxygen transfer in aerated tanks was previously identified only by the volumetric oxygen mass transfer coefficient (k_la) inside the water body [4, 5], whereas the little attention has been paid for the water spray despite oxygen transfer is predominantly in the water droplets. The occurring oxygen transfer have two phases; the dispersed phase of the water droplets in the continuous phase of atmospheric air. So there will be a different oxygen mass transfer coefficients for the water spray than that applied for the water body [2], where the oxygen transfer coefficient k_la is considered to represent all the occurred oxygen transfer in aeration according to the two-film theory [6].

The oxygen transfer in water bulk zone is related with many parameters, such as water level, tank and impeller geometry, rotation speed number of impellers and many operational conditions [7-9].

The theory of oxygen transfer in the surface aerated tank is very relevant to the flow profile that occurs within the tank. The improvement of the flow agitation enhances the contact area between liquid (water) and air phases [10] and the water spray profile above the water surface. The effective resistance to oxygen mass transfer takes place mainly in the liquid side of the gas-liquid mass transfer film; all other resistances in the system will be neglected. The oxygen mass transfer coefficient in the liquid, k_la is regarded as an indicator for mass transfer rate [11]. The gas-liquid contact interfacial area for oxygen mass transfer is very crucial in the rational design of gas-liquid equipment [12].

Undoubtedly the water sprays oxygen transfer is related with the droplets form and condition, where they propelled into the atmospheric air with relatively high discharge velocity [1]. The oxygen mass transfer coefficient is identified as spray (droplets) oxygen transfer coefficient k_la_d is investigated in this study. It is assumed that any other possible secondary mass transfer can occur is neglected such as the possibility of the Nitrogen gas transfer contained in the atmospheric air toward water droplets.

The employed saturation level is considered as the wet bulb temperature of the air, C_{ds} [13]. The basis used for this assumption is depending on the fact that the path of water droplets in the atmospheric air follows its own conditions of constant air composition, humidity, and temperature which is completely different from those existed in the water bulk. As a result, the higher equilibrium oxygen concentration can be reached theoretically for the droplet is the air wet-bulb temperature. The constraining factor controls how deep the wet-bulb temperature goes inside the droplet is depending on the droplet flight time, (the effect of flight time on water temperature is very limited as the droplets stays very short time in air in our case). Consequently the wet-bulb temperature prevails only at water droplet surface, while the inner droplet part temperature is highly affected by the relative high droplet velocity in the air and high heat transfer caused by this velocity, it remains generally at lower level than the surface temperature, while due to the inner motion the oxygen mass transfer inside the droplets is enhanced [14].

The used up-pumping flow agitator generates a flow pattern and means velocity fields in the aerated tank is produced due to the falling water droplets at the water surface. This creates a strong radial stream of the water and air bubbles near the water surface toward the walls. A part of the flow that drawn by the turbine blades is propelled as water droplets through the atmospheric air mostly by the vertical side of the turbine blades. No studies were made concerning the mean velocities profile of an aerated water inside such stirred tank similar to the configuration that applied in this study, which the mean velocity profile is affected by many factors like the tank geometry, impeller type and operation condition. Generally the studies were performed for the stirred aerated tanks with air supply sources [15, 16].

In this study like other work, the approach of turbulent flow regime in the liquid phase is applied in the same manner to water treatment aerated tank is investigated to determine velocity field and flow profile on the aeration efficiency and oxygen mass transfer in the water spray.

I. MATERIALS AND METHODOLOGY

A. Materials

A lab scale aerated system was built in the laboratory and is the perfect scale-down representation of the industrial system is illustrated in figure 1. An agitator turbine is used for mixing and aeration purposes with its up-pumping operation, where the turbine is placed at the water surface. In all cases, an acceptable mixing will provide good contact interfacial area between the contents. The surface aeration is achieved by water droplets projection with the rotation of the turbine and then the impingement for these droplets in water bulk and by water surface renewal due to eddies generation with the rotation. The number of blades of the turbine of is 12 (blades width 0.24 m), with diameter ratio D/T=0.24. Water height was kept constant at (H = 0.38T) is used by Issa [17].

In order to determine the velocity profiles and the occurred flow pattern inside the tank, the mean values of the different velocities are measured by PIV (Particle Image Velocimetry) as illustrated in figure 2. The PIV is used to study of the instantaneous flow field for both single phase and multiphase [17].

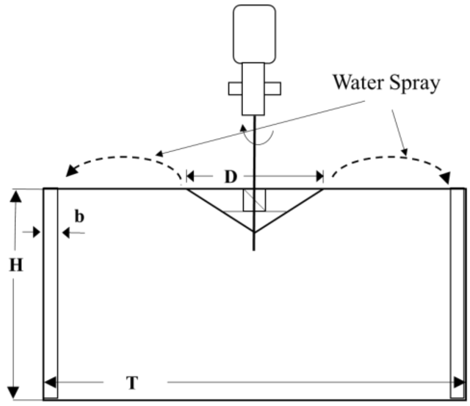


Figure 1. The schematic diagram of the experimental setup with presenting the projected water spray

B. Methodology

1. Water Spray Oxygen Mass Transfer

The calculated spray oxygen mass transfer coefficient $k_l a_d$ is based on several general assumptions: Each water droplet is totally well mixed, accordingly a uniform oxygen distribution within the droplets is obtained at any time when they crossed the atmospheric air to the water surface with no back mixing might. The dissolved oxygen concentration inside the droplet is related with the inlet concentration of the liquid body inside the tank. The outlet dissolved level of the droplet zone when the spray hits the water surface is considered as C_{dt}. The droplets volume and the mass transfer coefficient with the droplets oxygen saturated concentration are considered constant as illustrated in Equation 1.

$$C_{dt} = C_{ds} - (C_{ds} - C_{Lt}) \, exp(-k_l A_d \, t_f \, / \, V_d) \qquad (1)$$

The efficiency for gas-liquid contacting systems is evaluated by the commonly applied indicating factor called (Murphree contacting efficiency E_{md}) [18-20]. Murphree contacting efficiency is defined for various mass transfer operations as the efficiency of the occurred mass transfer operation due the contact of the gas and liquid phases as a ratio between the actual mass transferred to the ideal mass transfer [1]. In the aeration water spray and in other similar processes, the applied criterion for indicating the progressive oxygen mass transfer is same with the Murphree contacting efficiency and is called the spray aeration efficiency, E_{sp} [21, 22].

Equation 2 is for the contacting efficiency that can be varied from its minimum value 0.0 (i.e. no mass transfer occurred) to its maximum value of 1.0, which is an ideal condition that can be reached at an infinite time when equilibrium is attained between the water droplets and the atmospheric air [1]. The equilibrium level for the DO at the droplets outer surface depends on the air humidity is less than the saturation level in the water bulk. Hence, the saturation level is well represented by the wet bulb temperature than the normal DO saturation in the water; as the air temperature here differs from the water body temperature.

$$E_{sp} = \frac{C_{dt} - C_{Lt}}{C_{ds} - C_{Lt}} = 1.0 - exp\left(-k_l a_d \, t_f\right) \qquad (2)$$

Equation 2, the spray aeration efficiency relates the boundary levels for the actual and theoretical oxygen concentration gradients that take place from water droplets propelling position to the impingement with water surface location. to simplify the calculation of the oxygen mass transfer, equation 2 was rearranged as seen in equation 3 [1, 23]:

$$C_{dt} = (1 - E_{sp})C_{Lt} + E_{sp}\,C_{ds} \qquad (3)$$

Equation 3 shows that a plot between the resulted oxygen concentrations at the droplets impingement point with water surface at the corresponding recorded water bulk dissolved oxygen may give a straight line with a slope of ($1-E_{sp}$), and the intercept with ($E_{sp}\,C_{ds}$), to find a uniform basis for comparison purposes between the obtained results, by normalizing the calculated efficiencies to standard condition. The E_{sp} is corrected to the standard temperature condition, mostly of 20 ºC by applying the widely applied temperature correction relation is the Arrhenius type of water temperature correction. The following relationship is developed by many previous works, [24-28].

$$1-(E_{sp})_{20} = (1-E_{sp})^{(1-f)} \qquad (4)$$

Where f is the exponent determined by the following equation

$$f = 1.0 + 0.02103(T-20) + 8.261\times10^{-5}(\theta-20)^2 \qquad (5)$$

The standard spray oxygen transfer rate ($SOTR_{sp}$), depends on the water volumetric flow rate discharged by the turbine blades Q_{sp} for different range of discharges [1, 29] as shown in equation 6.

$$(SOTR_{sp}) = Q_{sp}(E_{sp})_{20}\,(C_{ds} - C_{Lt}) \qquad (6)$$

Water droplets are mainly discharged with a considerably high flow rate Q_{sp} according to turbine rotation speed used. The water droplets flow rate is regarded as an essential step for further droplets spray related calculations. Determining Q_{sp} by directly measuring turbine discharge velocity is complicated. The alternative way is applying the measurements to the hydrodynamic profile, more specifically around the turbine blades. In order to simplify Q_{sp} calculation, the total water spray droplets velocity can be feasibly represented by one value, wherein in turn the spray flow rate is constant.

2. *Hydrodynamic Profile*

The PIV was performed in order that flow patterns can be determined for the tank areas. PIV creates a laser sheet which allows us to inquire flow and velocity profile at various spatial parts inside the tank. LDV provides detailed information for single points with good temporal resolution while with PIV we can get detailed spatial information for different instants of time [30]. The obtained PIV measurements detailed information depends on the number of interrogation areas that divides the simultaneous images taken by used CDD camera after seeding tested liquid bulk with (Rhodamine) red fluorescent tracer particles (d_p=15 µm).

The formula of flow rate calculation is depending on the velocity component occurred within the controlled area as it explained with following equations [31]:

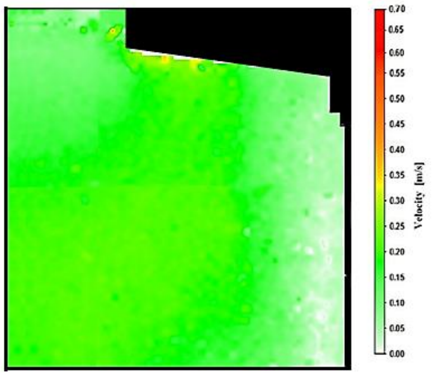
$$Q_{fr} = \pi D \int_{z-}^{z+} V_r\,(z)dz \qquad (7)$$

$$Q_{fz} = 2\pi \int_{r=0}^{r=R} rV_{z-}\,(r)dr + 2\pi \int_{r=0}^{r=R} rV_{z+}\,(r)dr \qquad (8)$$

II. RESULTS AND DISCUSSION

From equation 6 it is clear that the oxygen transfer in the water spray has a proportional relation with the spray flow rate Q_{sp}, the spray flow rate is in turn highly dependent on the rotation speed and the hydrodynamic profile inside the tank.

(a)



(b)

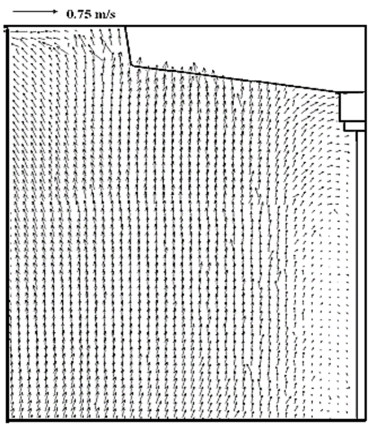


Figure 2. (a) The (r - z) velocities contour map for the turbine area inside the treatment tank. (b) The (r - z) flow field map for the turbine area inside the treatment tank, (the indicated 0.75 m/s in figure b, is the average for mean velocities in the entire tank) (the results were obtained from Issa [17]).

The effect of flow rate on oxygen mass transfer appears when changing the rotation speed the obtained oxygen transfer rate was changed for example at flow rate was changed from 0.0069 m^3/s (N=125 rpm) to 0.00885 m^3/s (N=150 rpm) the oxygen transfer rate raises to 0.0296 kg O_2/h. This fact has two trends one of them the initial DO concentration at the inlet of the water spray zone is in the same time DO in the water body, which is very relevant to mixing and flow pattern inside the tank. The other trend is that the quantity or in another word the flow rate of the generated spray is produced as a result of the combination of both the turbine agitation performance and the flow circulation loops created in the tank [17]. When we look at the velocity profile and the flow pattern near the turbine, the previously mentioned explanation could be understood more obviously as shown in figure 2.

To determine the water spray flow rate in a more accurate way, the flow balance around the agitator turbine can be made in the basis of that all the inward water flow to the turbine within the control volume is projected into the air as droplets (see figure 3). The control volume is chosen in the vicinity of the agitator turbine about 5mm near the vertical turbine blade width and at the height 250 mm at the level of turbine intake flow. The boundary lines of the control volume were chosen, as there is no deviation in the trajectories of the up flow mean axial velocities to any radial direction in the intake region. In our case, the flow balance around the concerned area would give the flow rate of the water spray since they were driven by the turbine blades toward the air and propelled as spray droplets. figure 3 illustrates the chosen control volume for the flow balance. The flow rate was calculated by applying equation 7 and 8 to determine all the inlet and outlet radial and axial flow rates to the control volume.

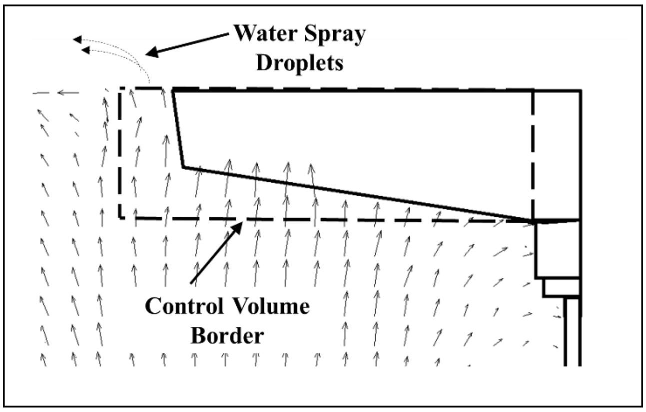


Figure 3. The control volume for flow balance at the vicinity of the agitator turbine.

The resulted standard aeration efficiency in the spray for the occurred hydrodynamic profile is shown in Table I, where it is noticed the water spray has a moderate aeration efficiency for the given rotation speed due to the high interfacial area with turbulent conditions [32]. The spray flow rate was calculated after implementing the flow balance for the specific area around the agitator turbine as mentioned before. Consequently, the standard oxygen transfer rate in the spray was calculated by equation 6. To obtain a more general view on the participation of the water spray in the whole oxygen mass transfer, it would be better to compare it with the oxygen mass transfer in the water bulk, hence the other it can be considered as a complementary or supplementary zone, where the accompanied mixing or agitation process are needed in order to accomplish distribution and diffusion of dissolved oxygen in the entire tank.

Table I. Water spray efficiency and the related measured parameters, t = 300 s.

N *rpm*	T_{bulk} *°C*	C_{ds} *mg/L*	C_{Lt} mg/L	E_{sp} -	$(E_{sp})_{20}$ -	Q_{sp} m^3/s	$SOTR_{sp}$ $kg\ O_2/h$
125	15.8	8.74	5.2	0.22	0.24	0.0069	0.0219

The SOTR in a water body for similar operating condition from data sets obtained by [17]. The SOTR had the value of 0.1617 kgO_2/h. this value represents the whole oxygen mass that transferred to water treatment tank. The OTR_{sp} is generally has excessed the percentage of oxygen transfer by (15 %) from the same reference [17]. The excess in the OTR_{sp} when is due to the improvement of flow pattern which is highly related to the oxygen mass transfer in the spray zone since the initial concentration of the DO in the spray zone is in the same time the final concentration of DO in the bulk zone. Hence, the more interfacial area between the water and air has been accomplished.

III. Conclusions

The results obtained for the water spray mass transfer zone lead to consider that an effective value for the mass transfer rate and aeration efficiency in the spray zone at 20°C with respect to operation conditions were achieved. For the water treatment tank, it is found that at the standard spray mass transfer rate $SOTR_{sp}$ and spray zone efficiency E_{sp} are highly related on the impellers rotation speed and consequently the hydrodynamic profile inside the tank. The majority of oxygen mass transfer is achieved in the water surface zone and in the water spray due to the high interfacial area and turbulent mass transfer occurred in this zone. The comparison between the oxygen transfer rates showed that a noticeable amount of the oxygen was transferred within the spray mass transfer zone about (15%). The discharge flow rate of the water spray Q_{sp} was calculated for the given turbine rotation by flow balance around the turbine. The $SOTR_{sp}$ (see equation 6) is relatively relevant to the time of measurement as long period of time the DO concentration in the spray will be closer to saturation.

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SYMBOLS

A_d	interfacial contact area of the water droplets, (m^2)
b	baffle width, (m)
C_{dt}	concentration of dissolved oxygen in water droplets at time t, (mg L^{-1})
C_{Lt}	concentration of dissolved oxygen in water at time t, (mg L^{-1})
C_{sd}	saturated concentration of dissolved oxygen in water droplets, (mg L^{-1})
C_t	concentration of dissolved oxygen at time t, (mg L^{-1})
D	turbine diameter, (m)
DO	concentration of dissolved oxygen in water
E_{md}	Murphree contacting efficiency for oxygen mass transfer, (-)
E_{sp}	spray mass transfer zone efficiency, (-)
$(E_{sp})_{20}$	standard spray mass transfer zone efficiency at 20 °C, (-)
f	temperature correction function to 20 °C for the spray mass transfer zone, (-)
H	water level in the tank, (m)
$k_l a_d$	volumetric oxygen mass transfer coefficient (Spray mass transfer zone), (s^{-1})
$SOTR_{sp}$	standard oxygen transfer rate in water spray mass transfer zone,(gO_2 h^{-1})
Q_{fr}	radial flow rate, (m^3/s)
Q_{fz}	axial flow rate, (m^3/s)
Q_{sp}	volumetric flow rate of the water spray, (m^3/s)
R	turbine radius, (m)
t_f	flight time of water droplets, (s)
T	Tank diameter, (m)
V_r	liquid bulk mean radial velocity (m s^{-1})
V_z	liquid bulk mean axial velocity (m s^{-1})
θ	Temperature, (°C)

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