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Effect of Water Column Height on the Aeration Efficiency Using Pulsating Air Flow

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Abstract

According to the United States environmental protection agency (EPA), a wastewater treatment plant is expected to remove at least 85% of the suspended solids and dissolved organic compounds from the wastewater before discharging it to a river or a lake. The aeration process is an integral part of any wastewater treatment plant, where suspended particles and dissolved organics are removed. The cost for aerating the wastewater is significant compared to other processes that take place in the wastewater treatment process. The normal operation of the aeration process is by compressing air continuously to basin diffusers, where the air is brought into contact with the water to provide the necessary oxygen for the microbial growth in the wastewater. Aeration systems utilize compressed air in pulsating flow mode have been proven to be more efficient than that of continuously compressed air. This study employs the wavy flow generated because of compressing the air alternatively (pulsating airflow) and investigate the effect of water column height on the oxygen transfer efficiency. Three water column heights are considered in this study, 0.6, 1.2 and 1.8 m, to investigate the effect of each water column on the SOTE at different airflow rates and pulsating times. The highest water column (1.8 m) gave better standard oxygen transfer efficiency (SOTE) results, but a better trend was observed for the lower water column at higher flow rates. The 1.2 m water column standard oxygen transfer efficiency was always taking an intermediate trend between the 0.6 m and the 1.8 m water columns SOTE. In addition, it was clearly shown that the best SOTE results for all water columns occur when the pulsating time equals 0.5 seconds.

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Keywords: *wastewater treatment, aeration, standard oxygen transfer efficiency, pulsating airflow, mixing in the aeration ta*.

Nomenclature

AAA	Amano Alkhafaji Alkhalidi parameter, $4Q/\pi D^2H$, 1/s
Co	Dissolved oxygen concentration at t = 0, mg/liter.
C∞	Dissolved oxygen concentration at saturation, mg/liter.
D	Diameter of water reservoir, m.
DO	Dissolved oxygen, mg/liter.
H	Height of the water column, m.
KLa	Overall mass transfer coefficient, 1/s.
KLa20	Overall mass transfer coefficient at 20ºC, 1/s.
OTE	Oxygen transfer efficiency.
OTR	Oxygen transfer rate, mg/s.
Q	Flow rate, L/min.
SOTE	Standard oxygen transfer efficiency.
SOTR	Standard oxygen transfer rate, mg/s.
t	Time, seconds.
T	Temperature, ºC
V	Volume of the water, liter.
$\dot{m}_{O_2}$	Mass flow rate of oxygen, mg/s.

1. Introduction

In secondary wastewater treatment, the aeration process has taken an important role, where the need for oxygen becomes vital to promote the microbial growth to suspend and efficiently separate the dissolved and suspended organic particles from the wastewater in the secondary clarifying treatment. Therefore, air and water need to be brought in contact in some container to have the transfer of oxygen molecules from the air to the water and provide the wastewater with the necessary oxygen for the aeration process. Two methods have been used in industry [1] to bring the air and water in contact; air diffusing systems and surface agitating systems. In the air diffusing systems, air diffusers are installed in a reservoir base. The compressed air is flowing out of these diffusers into the water in the reservoir. Surface agitating systems utilize the use of surface agitators to mix the water with the atmospheric air.

The air diffusing aeration system can be considered more efficient than the aeration system using surface agitation [1]. Nevertheless, both air diffusion and surface

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agitation are consuming the most significant portion of the energy for any wastewater treatment process as shown in figure 1, [2]. Therefore, the best aeration system is an aeration system that requires the minimum energy to operate, and such aeration system can have a significant impact on the energy cost of the aeration process and hence the water treatment process. The EPA [3] reported that not less than 85% of the biodegradable and total suspended solids should be removed from the wastewater before discharging it to the lakes or rivers. Due to the population increase and the expansion in industry, the wastewater capacity that needs to be treated increases. The EPA’s suggested technology increases the energy requirement for the aeration process to fulfill the EPA regulations. In other words, the energy consumption trend of the aeration process is growing with time. Therefore, it will be necessary to reduce that energy consumption by adopting new aeration design.

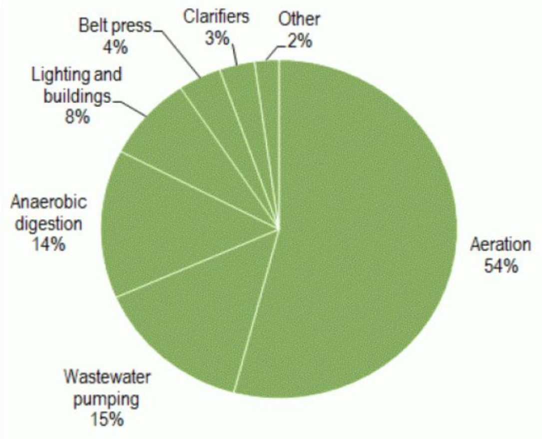

Figure 1: Energy consumption of a wastewater treatment process [3].

Many studies were made to optimize the aeration systems, but most of these studies discuss the effect of bubble size on the oxygen transfer rate between the air and water. The bubble formation is a very complicated process, and many mass transfer models have focused on the free rising of the bubble to determine the shape, surface area and the hydrodynamic behavior of the bubble. Higbie’s [4] penetration theory combines a hydrodynamic and mass transfer model to determine the shape and mass transfer of a single growing bubble.

The effect of gas flow rate on the bubbles frequency was studied by Das et al [5]. A needle-type conductivity probe was used to estimate the bubbles frequency. The study showed that the bubbles frequency is increased by increasing the gas flow rate.

Colombet et al. [6] considered the liquid side mass transfer coefficient in a dense bubble swarm for a range of gas-liquid volume ratio between 0.45 and 16.5%. This study was performed in a square water column to measure the bubble size, shape and velocity at different gas flow rates by using a high speed-camera. It showed that the bubble velocity decreases when increasing the volume fraction.

Dani et al. [7] used a non-intrusive technique consisting of a planar laser-induced fluorescence to measure the oxygen concentration of a bubble as it rises in the liquid. The study showed a distinguished increase in oxygen concentration at the bubble rising column while it is decreasing everywhere else.

Ashley et al. [8] conducted a bench-scale experimental study to examine the effect of four design variables on the oxygen transfer rate in aeration systems that uses fine pore diffuser. The study showed that the oxygen transfer rate is increased when increasing the airflow rate. A comparison between using a single diffuser and two diffusers for the same airflow rate showed that the oxygen transfer efficiency is higher when using two diffusers. The study used two different diffusers to create bubbles of 0.4 and 0.42 mm; there was no consistent effect of airflow rate on the bubble size.

Fujie et al. [9] investigated the spiral liquid circulation in a conventional aeration tank. The spiral liquid circulation rate at the liquid surface in the aeration tank was correlated as functions of the superficial gas feed rate, diffuser depth, and bubble diameter. It was concluded that the spiral liquid circulation rate increases the bubble velocity that increases the gas-liquid oxygen transfer.

Bubble size, bubble release rate and mixing within the tank was investigated by researchers [10-14]. It was found that the smaller bubble size, increased bubble release rate and improved and induced mixing to enhanc the oxygen transfer efficiency.

Recent research conducted by Alkhalidi et al. [15], have proven that pulsating airflow can enhance the oxygen transfer efficiency more than continuous airflow. The improvement is due to the generating waves because of the pulsating effect, which increases the mixing process between the air and water.

Alkhafaji et al. [16], considered the effect of pulsating airflow on the aeration efficiency for a range of airflow rate between 14 and 56 LPM. The study was conducted at different pulsating times. It was concluded that when using 0.5 seconds of pulsating time, the SOTE increased to about 50% more than that of continuous air flow.

The current study also focuses on how to increase the oxygen transfer rate between the air and water, but by augmenting the wavy flow in a water reservoir instead. This augmentation can be induced by using the pulsating air flow instead of the continuous airflow in the water reservoir and investigate the effect of the water column height on the oxygen transfer efficiency.

2. Methodology

The experimental set up for this study can be illustrated as shown in figures 2 and 3. The supplied air flows through a flow meter and a pressure gauge. Before it passes through the diffusers, the air passes through a control circuit, figure 2, this control circuit acts as an on/off switch to create the pulsating effect. Therefore, the air will diffuse alternatively from two air diffusers into the water. These are fine pore diffusers made of rubber, installed at the bottom of the water tank. The control circuit programmable software can control the time the air takes to diffuse into the water. The diffusers are connected with upstream solenoid valves, which are part of the control circuit, when one of the solenoids on, the other one is off and vice versa. This is the method used to create the pulsating or the alternating effect.

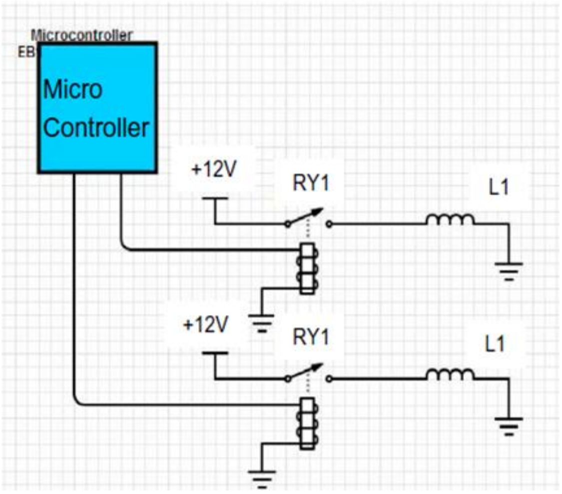

Figure 2: Control circuit [15, 16].

Three dissolved oxygen (DO) probes (see figure 3) were installed at different elevations along the water tank at different heights with an intermediate radial position between the two diffusers. These DO probes are used to measure the dissolved oxygen concentration in the water with 1 Hz frequency. They can measure oxygen concentration up to 20 mg/l within ±2% accuracy.

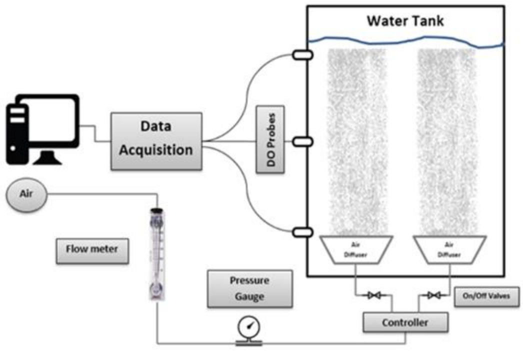

Figure 3: Experimental set up [15].

The oxygen concentration results obtained from these three DO probes were averaged for better accuracy to achieve the oxygen transfer efficiency (OTE). All the measurements are conducted under standard conditions, which include tap water, zero salinity, atmospheric pressure and 20ºC. Therefore, SOTE is the transfer parameter to be obtained in this analysis.

To obtain SOTE, the overall mass transfer coefficient needs to be determined first. This can be done by measuring the dissolved oxygen concentration in the water. In measuring the dissolved oxygen in the water, measurements should start with zero oxygen water; this means that oxygen should be removed from the water. The addition of sodium sulfite (Na_2SO_3) is used here to extract the dissolved oxygen and leaving the water with zero oxygen. Then, the overall heat transfer coefficient can be calculated by:

$$KLa = \ln((C\infty - C)/(C\infty - C0)/t \tag{1}$$

Equation 1 is used to calculate the overall mass transfer coefficient for the conditions when the water temperature is 20ºC. For temperatures less or greater than 20ºC, equation 1 should be corrected according to the following equation [17]:

$$KLa_{20} = KLa\theta^{(20-T)} \tag{2}$$

Where $\theta = 1.02$.

Then, the oxygen transfer rate (OTR), can be obtained by:

$$OTR = KLa\,V(C_\infty - C_0) \tag{3}$$

Finally, The OTE can be calculated by using:

$$OTR = OTR/\dot{m}_{O_2} \tag{4}$$

SOTE is the transfer parameter used for this study, which is the measure of how efficient the aeration system is. Therefore, equation 4 becomes:

$$SOTE = SOTR/\dot{m}_{O_2} \tag{5}$$

3. Results

The SOTE is the transfer parameter that reflects the effectiveness of the aeration process. Therefore, the goal of the current study is to obtain the SOTE results for each water column at different pulsating times. Three pulsating times are considered: 0.5, 1.5 and 2.5 seconds. Increasing water column on top of air membrane includes an increase in water tank volume, larger water tank volume requires higher airflow rate to aerate this water. A ratio parameter between airflow to tank size parameter, called Amano Alkhafaji Alkhalidi (AAA), will be introduced for best data rendering. The AAA, see Eeq. (6), the parameter will be used to compare the SOTE results for different water column heights in the first part of the results discussion (figures 4 to 6). The second part (figures 7 to 9) relates the SOTE with the flow rate at different pulsating times.

$$AAA = 4Q/(\pi D^2 H) \tag{6}$$

Where:

Q= Airflow rate, L/min.

D= Tank diameter, m.

H= Tank high, m

First, the SOTE investigation was carried for each water column at different pulsating times, SOTE results will be compared to different water columns at each pulsating time. Figures 4, 5 and 6, show the SOTE variation with AAA for 0.6, 1.2 and 1.8 m water columns respectively.

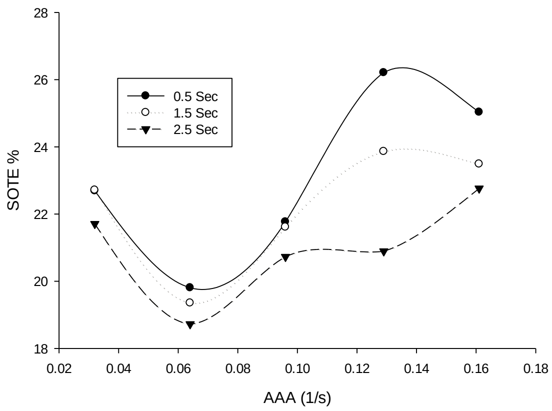

Figure 4: SOTE variation with AAA parameter for 0.6 m water column.

Relatively similar behavior for all pulsating times can be noted from figure 4, where the SOTE decreases as AAA increases from 0.03 to 0.064 1/min. The SOTE keep increasing between 0.064 and 0.13 1/min. Beyond 0.13 1/min, the SOTE decreases again for all the pulsating time cases except the 2.5 seconds pulsating time case, where the SOTE increases.

Figure 5, shows the SOTE variation with AAA when the water column equal to 1.2 m. Figure 5 gives similar behavior to that of Fig. 4, except for the region when AAA ranges between 0.074 and 0.093 1/min. The SOTE is increasing for the 0.5 and 1.5 seconds cases, but it decreases for the 2.5 seconds pulsating time.

The last figure to show in the first part of the results in figure 6, which is the case when the water column is 1.8 m. In this figure, the SOTE follow a similar trend as in figures 4 and 5 between 0.012 and 0.046 1/min, except the case when the pulsating time is 2.5 seconds. Beyond 0.046 1/min, the SOTE is decreasing for all pulsating times.

Figures 7, 8 and 9, show the SOTE variation with flow rate for the three water columns when the pulsating time equals to 0.5, 1.5 and 2.5 seconds, respectively.

Figures 7 and 8 show similar trend, where the SOTE decreases when the flow rate increases from 14 to 28 L/min and then it increases between 28 and 56 L/min. When the flow rate increases from 56 to 70 L/min, the SOTE for both the 0.6 and 1.8 m water column is decreasing while it is increasing for the 1.2 m water column.

When comparing figures 7 through 9, they clearly show similar trends when the flow rate increases from 14 to 42 L/min. After that, the SOTE trend tends to be less steep for the higher water column as the pulsating time increase. However, the case is opposite to the lower water column.

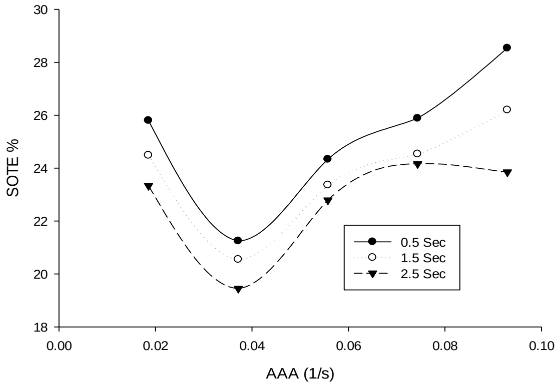

Figure 5: SOTE variation with AAA for 1.2 m water column.

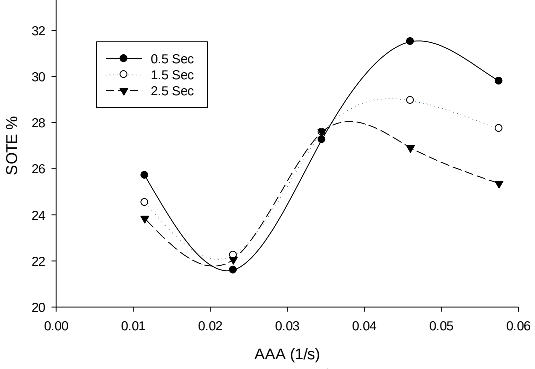

Figure 6: SOTE variation with AAA for 1.8 m water column.

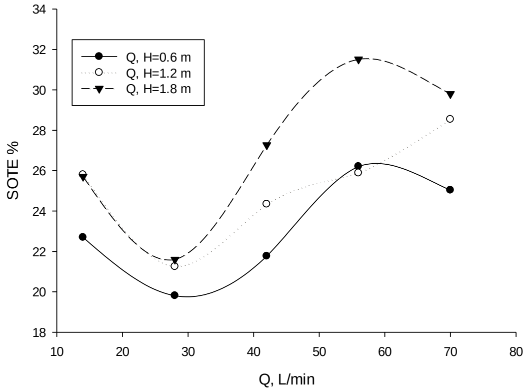

Figure 7 SOTE variation with flow rate for 0.5 seconds pulsating time.

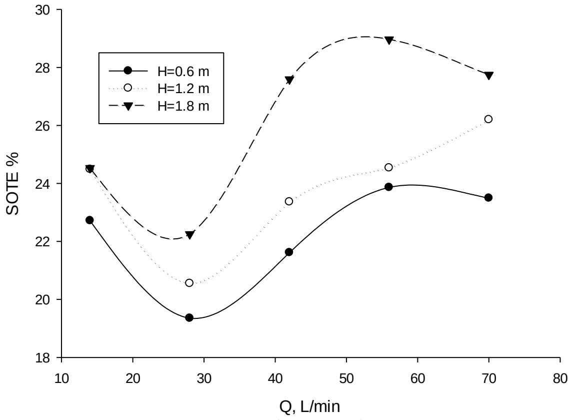

Figure 8: SOTE variation with flow rate for 1.5 seconds pulsating time.

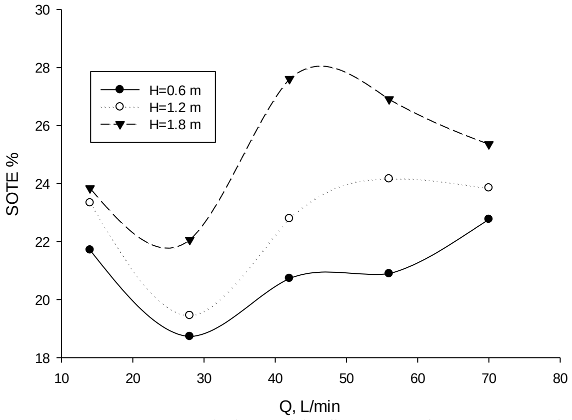

Figure 9: SOTE variation with flow rate for 2.5 seconds pulsating time.

It is noted from the SOTE results that they all start with high SOTE then it decreases. This pattern is because, at a very low flow rate, the SOTE is relatively high since the SOTE is inversely proportional to the oxygen flow rate and hence the air flow rate. Then the SOTE experience an increase when the flow rate increases beyond 28 L/min, which is attributed to the mixing contribution due to the wave generated from increasing the flow rate that helps to increase the mass transfer between the air and the water.

Based on figures 7 through 9, it is noted that the higher SOTE can be considered to occur when using a higher water column (1.8 m). The lowest SOTE is given when using the lowest water column 0.6 m. Nevertheless, it is evident from figures 7, 8 and 9 that, the SOTE trend is increasing for the lowest water column while it is decreasing for the highest water column at higher flow rates and vice versa at lower flow rates. This means that the waves created in the lower water column case (0.6 m) can be considered to have a more significant effect than those produced in the highest water column (1.8 m) at higher flow rates. This behavior is particularly observed when the pulsating time is 2.5 seconds, where all the SOTE results are tending to approach each other. In addition, it is noted that, in the case of the 1.2 m water column, the SOTE always represents a median between that of the higher and the lower water column for all ranges of flow rates and at any pulsating time.

Figures 10 and 11 show the surface waves generated for the 0.6 and 1.2 water columns when the pulsating time is 2.5 seconds. The 0.6 m water column gives the highest surface wave that can be measured approximately 7 cm high. For the 1.2 m water column, the surface wave is a little lower than that of the 0.6 m water column, which is approximately 3 cm. The 1.8 water column showed very low surface waves that can be insignificant.

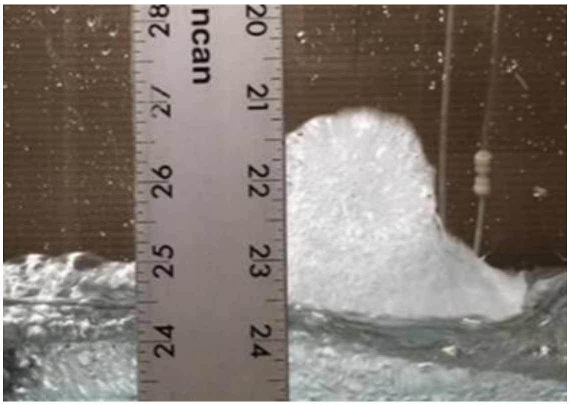

Figure 10: Surface wave generated for the 0.6 m water column

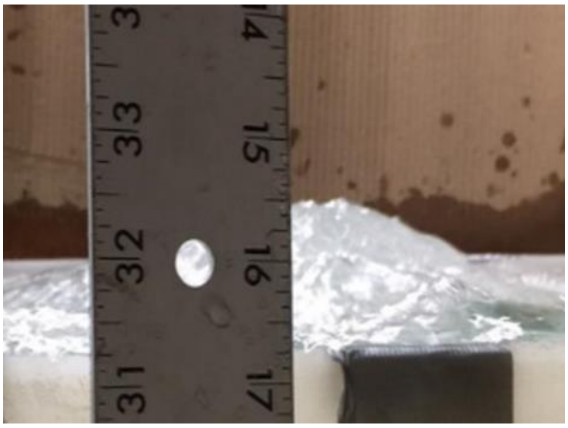

Figure 11: Surface wave generated for the 1.2 m water column

Therefore, the surface wave generation is depending on the height of the water column. It is attributed to the balance between the lift and the drag forces acting on the bubbles [18], which determines the resident time of the bubbles in the water. A study to determine the relation between the resident time and the water column height is suggested since this study is not discussed in the current paper.

SOTE measurements uncertainty analysis was performed for the 1.2 m water column height. The uncertainty of the measurements for that case is ranging between ± 3.9 and ± 0.05 % as shown from Table 1.

Table 1: Measurement uncertainty of SOTE for the 1.2 m water column

		Pulsating time (seconds)		
		0.5	**1.5**	**2.5**
Flow rate (L/min)	**14**	± 0.032	± 0.023	± 0.013
	28	± 0.012	± 0.002	± 0.039
	42	± 0.025	± 0.0005	± 0.015
	56	± 0.015	± 0.035	± 0.038
	70	± 0.023	± 0.021	± 0.033

4. Conclusion

The SOTE results for the 1.8 m water column is the highest among all the water columns. The lowest SOTE results are obtained with the 0.6 m water column. An intermediate behavior is observed when considering the 1.2 m water column. Also, the highest SOTE can be found when the pulsating time is 0.5 seconds; this applies to all the water column cases. The higher SOTE when using, the higher water column can be attributed to the rising velocity of the bubbles, which becomes low compared with the lower water column. In this case, the bubbles will stay longer in the water, and the oxygen transfer process from the bubble to the water will take longer time. Therefore, better oxygen transfer rate is experienced as the water column becomes higher than 0.6m. On the other hand, another important factor that has been observed to affect the results, particularly for the lower water column, that is the effect of the airflow rate. The SOTE results tend to trend better than that of the higher water column at higher flow rates. Therefore, there can be a better potential for improvement when considering lower water column with higher flow rates.

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