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Experimental Study of the Liquid Film Flow on Rotating Disc Contactor of Rough Surface Partially Immersed in Liquid Bath

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Abstract : Several studies related to the viscosity liquid film flow on the surface of a flat disk that rotated vertically have been done by other researchers, both experimental and numerical models. But the difference is that, this study using tap water with low viscosity. In addition this study analyzed the influence of surface roughness factor on the profile of liquid films. In this study, the liquid film thickness profile was measured when it was dragged to follow the vertically rotating disk. The disks were distinguished between hydrophilic and hydrophobic. In some literature, it is explained the factors that influence the thickness of liquid film is the radius of the disk, the angular velocity, viscosity and surface tension. Furthermore, in this study, it was identified that the thickness of liquid film is also influenced by the surface roughness of the disk. The results showed that the liquid film was able to attach well on the hydrophilic surface compared to hydrophobic one. In addition, the liquid film thickness profile was also more evenly to the edges of the disk and was able to reach the top when the disk emergence from the liquid surface in the trough.
Keywords : liquid film, vertically rotating disk, surface roughness.

Introduction

The liquid film flows are encountered in awide range of industrial aplications. An example is the mass transfer study in Rotating Biological Contactor, in which that the waste water treatment process. The disc is partially immersed in the water. As a consequence of the rotation, a liquid film is brought upwards over the surface of the discs, thus providing a contact of the film with the gas phase above the water. After moving downwards the liquid film will be taken up again by the bulk of the water in the trough. In mass transfer studies on rotating discs of Bintanja et al., 1975 and Zeevalkink et al, 1978[4,14], the thickness of the liquid film on the discs playa an important role, particularly at low rotational velocities.

Unlike the thin film flow on a horizontally rotational disk, the liquid film flow on a vertically rotational disc partially immersed in liquid is always associated with a meniscus region where the liquid is dragged out by the disc moving and a specially oscillating region where the film formed on the disc is dragged into the liquid.The geometric constraint of a solid surface, as well as the interactions between water and the solid, lead to structural changes of water compared to its bulk properties. It is accepted that surface roughness, surfacewettability influence the interaction between liquid and solid at the interface[1,2,3,5,7,8,9]. Surface can be divided into two classes according to their affinity to water: hydrophilic (water attracting) and hydrophobic(water repellant)[16,21].

In a rotating disk contactor, the disc are partially immersed in the water. As a consequence of the rotation, a liquid film is brought upwards over the surface of the discs, thus providing a contact of the film with the gas phase above the water. After moving downwards the liquid film will be taken up again by the bulk of water in the trough. The recirculated water film will be homogeneously mixed with the bulk of the liquid.

The thickness of the liquid film on the discs plays an important role, particularly at low rotational velocities in mass transfer studies. The withdrawal of flat plates from liquids has been examined thoroughly, both experimentally and theoretically[14]. The flat plate withdrawal theory[12,14] states that withdrawal of a smooth infinitely long flat plate from a liquid with a velocity results in an adhering film of thickness δ which can be calculated as a functi on of the effects of gravity, withdrawal velocity and physical properties of the fluid. This maybe expressed as follows:

$$\delta = K\left(\frac{\eta\omega R}{\rho g}\right)^{1/2} \qquad (1)$$

Where, δ is*liquid film*thickness(μm),ηis dynamic viscosity of water ($kg.m^{-1}.s^{-1}$), ρis density of water ($kg.m^{-3}$), ωis angular velocity (rpm), R isradius of disk (m). The connection between δ with $\omega^{0.5}$ is linear.In mass transfer of oxygen, the values in this case is directly dependent on the actual film thickness (δ)[4,15,17,20]. Zeevalkink et al[14] made an independent study and obtained a theoretical derivation for the film thickness δ on rotating discs based on the flat plate with drawal theory. In the author experiments to determine the thickness δ, the method of volume was used[14].

The amount of water entrainedby the discswas measured by holding sponges against one of the discs (along the surfaces which is not submerged, this is called the thickness area of ultimate film), see Figure 1. Thus, the formula becomes:

$$\delta = \frac{M}{\rho\pi(R^2 - H^2)} \qquad (2)$$

Where M is weight increase (gram)

The author related δ to bea function of the rotational velocity as well as depth of immersion in addition to the forces of gravity and viscosity.The author explained that the disk rotation speed was the speed of the vertical peripheral disk. It was a function of rotation speed and the depth of the disk. It also fitted the experimental data, with a correlation coefficient of 0.99[4]. Therefore, equation(1) has been used for the theoretical calculation of average δ values over the exposed disc surface in the model.

The determination of the thickness of the liquid film on the vertically rotating flat disk, continued by Sanjay[11], using Laser Distance Sensor to measure the thickness of the liquid film. It was proved that larger disc diameter need more peripheral speed[1,11]. The studies above, not to consider the factor of surface roughness and its influence on the thickness of the liquid film attached to the disk when it is out of the water surface. In this study the thickness profile of the liquid film on the rough disk surface was used, to determine the thickness of liquid film on the disc.

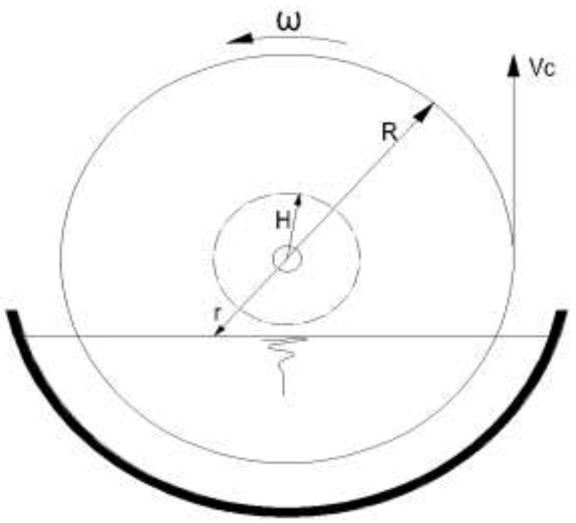

Figure 1. Scheme of rotating disk

Experimental

Material and Instrumentation

The material of experiment was tap water, the water maintaik keep at 26°C (σ = 2.69 .10^{-3} N/m, ρ = 996,81 kg/m^3, μ = 0,8746.10^{-3} kg/m.s)

The laboratory scale RDC consisted of a semicircular trough. The tank was divided into one disc of equal volume. The disc on a one-meter horizontal shaft which traversed the length of the trough (see Table 1).The disk material consisted of acrylic and novotex O (which represented a hydrophobic surface), and novotex I (which represented a hydrophilic surface, outer layer novotex was removed). The discs immersion depth was varied by changing the water level.Due to practical reasons only the outer discs were used for the measurements. The water temperature was kept at 26°C.

Table 1. Reactor design and operating parameters for laboratory scale

Specifications	Dimensions
Number of discs	1
Mutual distance of discs (m)	0.02
Diameter of discs (m)	0.23
Thickness of discs (m)	0.01
Rotations per minute	1; 3; 5; 7.5; 10; 15; 20
Depth of immersion under from centre of disc (m)	0.025 ; 0.063 ; 0.07
Depth of immersion above from centre of disc (m)	0.023
Distance between outer disc and trough (m)	0.020

In Figure 2. Scheme of rotating disc apparatus with a single disc. The materials of disc were varied, such as acrylic, novotex O and novotex I.

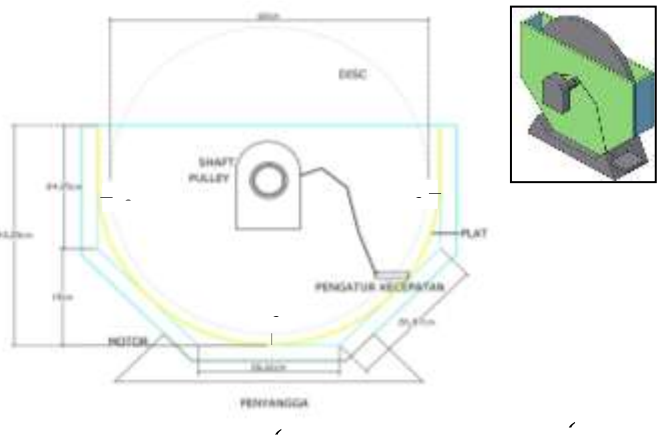

Figure 2. Scheme of rotating disc apparatus

For each surface material variation, atomic photo, using atomic force microscope (AFM), was performed to determine surface roughness(Nanoscope Iia, Digital Instruments, Vecco, Metrology Group). AFM image was obtained in laboratory conditions with 1 Hz scan rate and 1,0x1,0 μm^2 scan size. This method worked well on the material which particle size was determined to its height.

The Liquid Film Thickness Determination on Flat Disc

In this study, to measured the thickness of the liquid film, using a sponge media [14]. This is due to the average thickness of the liquid films in this study, below 100μm. So that the sensor devices commonly used, were not able to measure precisely, because of the limitations of the tool. In this work the amount of water entrained by the discs was measured by holding sponges against one of the discs (along the wetted area in Figure 1, which is in the region of ultimate film thickness). After one or two rotations the increase of weight increase (M) per rotation the mean film thickness was calculated. The water was equally spread over the disc and that the film velocity equals the velocity of the disc

Results and Discussion

The Liquid Film Thickness Profile Terms of The Disc Material

The data testing and statistical factorial designs related to disk material effect on the thickness of the liquid films has been performed. From the data testing, there was significant differences in varied the material of disc. In this section, the thickness profile of the liquid film in each material was viewed by varying the depth and the square root of the angular velocity of disc. Figure 3 the thickness profile of the liquid films when viewed from different types of materials. The results of the thickness of liquid film in acrylic, novotex O and novotex I were: 0.138 to 38.866 μm; 0.982 to 41.415 μm and 12.280 to 76.115 μm respectively. This thickness profile of water at 20^oC, ρ= 0.99823 gr/cm^3 andυ=1.00 x 10^{-6} $m^2s^{-1}$was lower than those reported in literatures[4,11,14]. This was due to the different water properties and the diameter of the disk (R),is larger in the literature. The radius of the larger disk would indicate the reduction of shear effect, so that the peripheral speed and centrifugal force were higher.

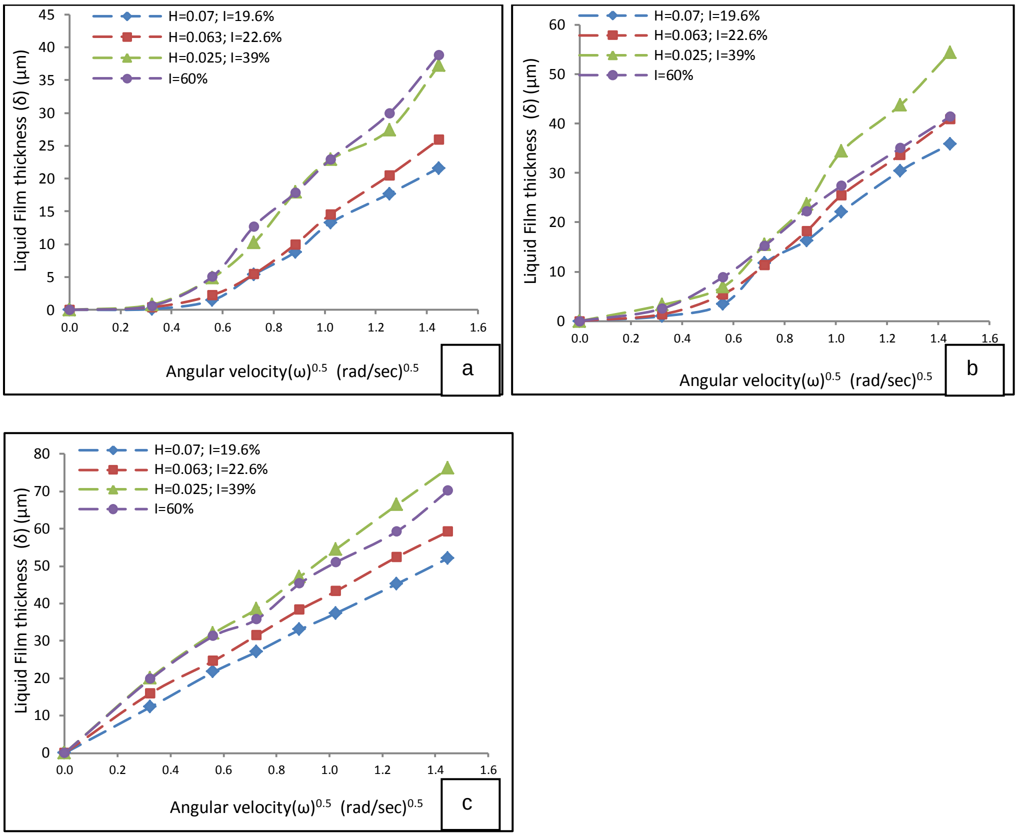

Figure 3. The thickness of *liquid film* on the surface of (a) acrylic; (b) novotex O and (c) novotex I materials

Figure 3 showed the tendency of the thickness of the liquid film on the acrylic material and novotex O, based on the relation between δ_{rf} with the root of disk rotation speed was non-linear. If plotted with polynomial equation, the determination coefficient (R^2) was more than 99%. On novotex I material, the connection between δ_{rf} with the root of disk rotation speed was linear. The conditions applied to variations in water depth below the pivot disk and had a determination value of R^2, the average was above 99%. While on the water depth above the pivot, in this case 23 cm above the pivot (60%), the tendency of the relation was nonlinear. The equation applicable was polynomial equation, with R^2 99.8%. The correlation was not in accordance with the equations used by Bintanja et al.,and Zeevalkink et al.,[4,14]. However, it was in line with the approach used by Avanasiev et al.[1].

The Influence of Surface With Hydrophilic and Hydrophobic Nature To The Thickness of Liquid Film

The factors of disk material types needed to be calculated in the determination of the characteristics of the liquid film thickness. The types of material surface related to water contact were divided into hydrophilic and hydrophobic surface. The difference was if the surface of the material was hydrophilic, the water would be easier to be dragged and would attach well on the disk. Thus, no-slip condition occured on the solid hydrophilic surface, which the disk rotation speed was assumed equal to the speed of liquid films rotation[14]. On the contrary, the water attached to the slip condition on hydrophobic surface. This would be more clearly explained in the visualization below, Figure 4.

(a) (b) (c) (d) (e) (f)

Figure 4. The visualization of the Liquid Film Dragged by the Disk When It was Out of The Water Surface, (a)&(b) *Acrylic* Material. w=5 & 20 rpm;(c)&(d) NovotexO w=5 & 20 rpm; (e)&(f) Novotex I, w=5 & 20 rpm;

In Figure 4, the profile of liquid film on the surface of the hydrophilic and hydrophobic. Hydrophobic surfaces were represented from acrylic material and novotex O. On acrylic material, the water was easy to slip when it was dragged onto disk. At 20 rpm, the water could not meet the entire area of the disk exposed, the value of r (the radius of the water dragged by the disk) was only half of the field exposed. On the novotex O material, it was much better in dragging water than acrylic, but at a lower rotation speed (w = 5 rpm) liquid film remained difficult to attach on the disk. At novotex I material, water could attach well on the disk. Therefore, if the rotation speed was increased, the water thickness was appeared to increase. Thus, the theory described by Avanasiev et al., (2008) could be clearly illustrated. However, there were water diffusion factors on the surface of novotex I, so when the water was cleared, it was still left behind on novotex I, it took approximately 1 minute to dry back in.

The Characteristics of Disk Material Surface Roughness.

Characterization of disk material surface roughness was as an initial evaluation of the lubrication process of liquid films on the disk. It was related to the nature of solid to liquid, the wetness system that were hydrophilic and hydrophobic. One of the instruments that could be used to characterize in nano-meter size was Atomic Force Mycroscopy (AFM). The instrument was chosen because it had a high ability to study the nature and structure of nanoscale materials [6]). In Figure 5 the results of AFM photo to the contact surface of acrylic, novotex O and novotex I.

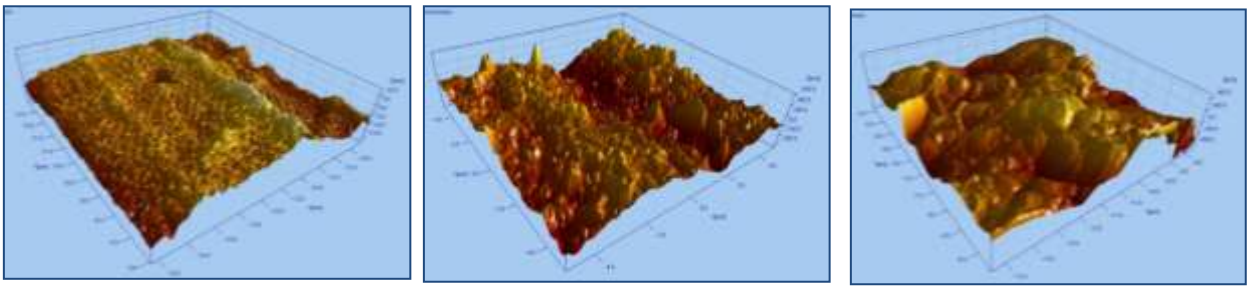

Figure5. AFM image at material (a)*Acrylic*; (b) *Novotex O* dan (c) *Novotex I*, with the*scan range 5,0x5,0*μm^2

The characterization of surface materials in this study was only evaluated from the material surface roughness profile only. These factors included vertical deviation of arithmetic average roughness (Ra), the standard deviation of the Ra (RMS), the height of maximum particle (Rmax) and the distance between the top end to the end of the valley (PV).

Nanostructure of the third disk material was observed on the value of some parameters. The measurements results of analyzed parameters could be seen in Table 2. The roughness parameters value on the three disk materials.

Table 2. The roughness parameters value on the contact surface of acrylic, novotex O and novotex I.

No	Parameter	Average Thickness of Liquid Film (δ_{rf})				
		Acrylic	Novotex Outside		Novotex Inside	
1	Ra (nm)	2,152	50,907	57,572	88,352	95,262
2	RMS (nm)	1,625	32,497	34,593	46,760	47,620
3	Rmax (nm)	7,750	117,308	125,443	177,143	190,769
4	PV	14,000	225,000	196,107	328,572	338,461

The results of the above surface roughness parameters provided information about the surface characteristics of the depth or height which was not evenly distributed. From the table, it appeared that there were differences on the surface roughness of the three disk materials. The lowest roughness value were found on the acrylic material. Novotex O material had a higher surface roughness than the acrylic materials, but lower than novotex I. It also affected the thickness of the liquid film which averaged at around 2-43µm. While on novotex I, it had the highest roughness parameters value with the thickness of film liquid which averaged in the range of 17-64µm. In Figure 6 explain about the effect of surface roughness to the thickness of liquid film.

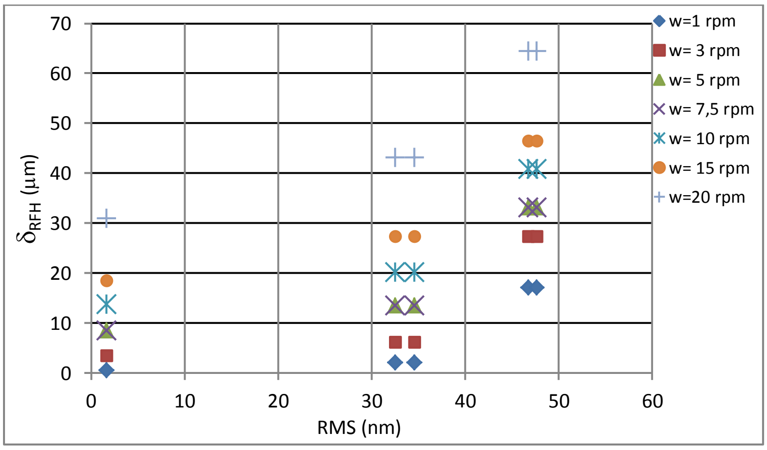

Figure 6. The Connection of Roughness Surface (RMS) With the Average Liquid Film (δ_{RFH}) Calculation A_{wetted}

From the calculation of surface roughness, it was found that the lowest RMS value was acrylic material, i.e. 1.625 nm. This was proven in experiment results using acrylic material, the liquid film dragged onto the disk at 1-7.5 rpm had uneven thickness. It meant at the beginning it was dragged out, the liquid film slightly thickened, then it slipped back down. Therefore, it was difficult to detect the thickness, the shape was only few drops in some places. At 10-20 rpm, the thickness of the liquid film was more constant and easily detected. The liquid film thickened when it was dragged out and the thickness was still detected from the top to drag in. Nevertheless, the liquid film was still unable to reach the edge of the disk.

In novotex O, where the outermost layer of novotex was used as a medium of contact, the RMS value was in the range of 30, it was greater than the surface roughness of acrylic media. However, the thickness of liquid film was thin and uneven on the disk at 1-5 rpm. At 7.5 - 20 rpm, the liquid film began to look thickened and spread, but it was still unable to reach the top disk. Some of the flow of liquid film was dragged in, some flowed downward.

The RMS value on novotex I was bigger than the other two materials. Besides the higher roughness parameters, the porous surface characteristics made it different from acrylic material and novotex O. Thus it was possible to have no slip liquid films in the process of dragging onto disk.

Different characteristics in the three materials when grouped by wettability, the acrylic material and novotex O were impermeable. It was permeable on novotex I with its porous surface. The pores allowed the diffusivity only on the surface.

Conclusion

The thickness profile of the liquid film could be solved well. Based on the experiment results, there were several factors that dominated and was related to the thickness profile of the liquid film. The dominant factors that affected the thickness of the liquid film were the viscosity, surface roughness, rotational angular velocity, and the depth of the disk. The thickness of the liquid film was significantly increased with the increasing of rotational angular velocity, which was in line with the literature.

Besides the rotational angular velocity, the thickness of the liquid film increased with the increasing of the surface roughness, viscosity related to the temperature. The factors of surface roughness was related to the liquid film which was able to attach to a solid surface with hydrophilic or hydrophobic nature. It was found that the thickness of the liquid film increased on the bigger surface roughness and the hydrophilic solid surface. Whereas on a hydrophobic surface, the bigger surface roughness also made the thickness of the liquid film increased, such as in the surfaces of novotex O and acrylic materials.

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References

1. Afanasiev, K., Munch, A., Wagner, B., Thin film dynamics on a vertically rotating disk partially immersed in a liquid bath, Science Direct, Applied Mathematical Modelling,2008,32; pp. 1894-1911
2. Bonaccurso, E., Kappl,M., Hydrodynamic force measurements: boundary slip of water on hydrophilic surfaces and electrokinetic effects, Phys Rev Lett, 2002, 88,076103
3. Bonnaccurso E., Butt H,J., Surface roughness and hydrodynamic boundary slip of a Newtonian fluid in a completely wetting system, Phys Rev Lett,2003, 90,144501
4. Bintanja, H.H.J. Erve, J.J.V.M, Boelhoewer, C., Oxygen Transfer In arotating disk treatment plant, Water Research1975, 9, 1147-1153
5. Choi, C, H., Westin, K.J., Apparent slip flows in hydrophilic and hydrophobic microchannels, Physical Fluids 2003,15,2897-2902
6. Guriyanova,S., Semin,B., Rodrigues,T.S., Hydrodynamic drainage force in a highly confined geometry: role of surface roughness on different length scale, Microfluid Nanofluid, 2010, 8, 653-663
7. Maali, A., Cohen-Bouhacina,T., Measurement of the slip length of water flow on graphite surface, Appl Phys Lett, 2008, 92,053101
8. Pit, R., Hervet, H, Direct experimental evidence of slip in hexadecane: solid interfaces, Phys Rev Lett, 2000, 85,980-983
9. Qian,T.,Z., Wang, X.P., Hydrodynamic slip boundary condition at chemically patterned surfaces: a continuum deduction from molecular dynamics, Phys Rev E, 2005, 72,022501
10. 10.Rittmann, B.E., Suozzo, R., Romero, B.R., Temperature effects on oxygen transfer to Rotating Biological Contactors, J.Water Pollution Control, Fed.1983, 55:270-277
11. Sanjay, Dutta,Mathematical modelling of the performance of a rotating biological contactors for process optimisation in wastewater treatment, Dissertation, Karlsruhe,2007
12. Schlichting, H., Boundary-layer theory, McGraw-Hill Book Company, Sixth Edition, New York, 1968
13. Truesdell R, Mammoli A., Drag reduction on a patterned superhydrophobic surface, Phys Rev Let,2006, 97,044504
14. Zeevalkink J.A., Kelderman,P., Visser,D.C., Boelhouwer,C., Liquid film thickness in a Rotating Disc Gas-Liquid Contactors, Water Research,1978, 12:577-581
15. Zeevalkink J.A., Kelderman,P., Visser,D.C., Boelhouwer,C., Physical Mass Transfer In Rotating Disk Gas-Liquid Contactors, Water Research 1979, 13,pp.913-1919
16. Zhu Y.X., Granic, S., Limits of the hydrodynamic no-slip boundary condition, Phys Rev Lett,2002, 88: 096102
17. Boumansour, B.E. dan Vasel J.L, A New Tracer Gas Method To Measure Oxygen Transfer and Enhancement Factor on RBC,Water Research 1998,Vol 32, No. 4, pp 1049

18. Krechetnikov, R. and Homsy, G.M. Dip Coating In The Presence of a Substrate Luquid Interaction Potential, Phisics of Fluids 2005,17.
19. Landau L., Levich B., Dragging of a Liquid by Moving Plate, Acta Physicochimica U.R.S.S, 1942, Vol.17, No.1-2.
20. Palma, L.D., and Verdone, N., The Effect of Disk Rotational Speed on Oxygen Transfer In Rotating Biological Contactors, Bioresource Technology 2009, 100; 1467-1470.
21. Perry, A.E.,Schofield, W.H. and Joubert, P., Rough Wall Turbulent Boundary Layers", Journal of Fluid Mechanics, 1969, Vol.73, pp. 383-413.

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