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A Parabolic-Curvilinear Reverse-Flow Air-Flotation System (PAF) for Removal of Suspended Solids in Sago Starch Production Wastewater Effluents

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Abstract

A Parabolic-Curvilinear Reverse-Flow Air-Flotation Treatment System (PAF) was recently developed for the removal of total suspended solids from sago starch production wastewater effluents. The primary components of the system consist of a parabolic-curved plate, a series of water pumps, an air curtain and valve-froth collection plates to repeat bubbling treatment in a gradually increasing movement flow. Performance tests were carried out by using synthesized sago wastewaters. Performance tests were carried out to determine the total suspended solids and turbidity removal efficiencies. Total suspended solids of the synthesized sago wastewaters ranged from 95 to 515 mg/L, 86.9 to 413 NTU for turbidity and 5.44 to 7.43 for pH. The total suspended solids and turbidity removal efficiencies of this system were found to be proportional to residence time, and inversely proportional to influent flowrate. The highest achievable total suspended solids and turbidity removal efficiencies for this treatment system recorded 85.63% and 77.89%, respectively. The presence of parabolic-curved plate in the system could improve the removal efficiencies as high as 34.22% for total suspended solids and 37.82% for turbidity. The system performance can further be improved by 13.65% for total suspended solids removal and 24.49% for turbidity removal with the installation of air curtain whilst 9.04% for total suspended solids removals and 6.03% for turbidity removals with the installation of water pumps in the system. Additional 17.2% of total suspended solids and 3.1% of turbidity level removals could be achieved by application of chemicals, i.e., alum and sodium aluminate.

Keywords Air Flotation, Total Suspended Solids, Sago Factory Wastewater Effluents

Nomenclature :

AC	Air curtain
PAF	Parabolic-curvilinear reverse-flow air-flotation treatment system
PC	Parabolic-curved plate
Pa	Water sample taken at the inlet of PAF system
Pb	Water sample taken before the air curtain zone and after the water pump zone of PAF system
Pc	Water sample taken at the outlet of PAF system
Pd	Water sample taken on water surface of froth collection corner of PAF system
WP	Water pump

INTRODUCTION

Sago palm (*Metroxylon Sagu*) was found to be the premier starch producer among the starchy crops of the world, especially in tropical countries [1;2]. Due to good market price (US$ 500 /tonne) for sago starch, more sago processing operations are expected and wastewater effluents (200,000 to 300,000 tonnes per annum globally) generated are magnificently folded [3;4]. Wastewater effluents generated from a sago factory that operating 6-7 days per week and 24 hourly are voluminous with an average effluent discharge rate of approximately 30 L/min (1.8 tons/hr) [5]. Rapid development in sago and starch production industries has left various environmental impacts, especially water pollution problem to the environment. However, only few of the factories have implemented wastewater treatment facilities for environment conservation purposes as this is most probably due to high energy/cost input (20% to 50% of the total starch production cost) and unreliable treatment efficiency although they are aware of the need for such measures [6;7;8;9;10;11;12;13;14]. High concentration of total suspended solids (66 to 12,936 mg/L), biochemical oxygen demand (900 to 3,444 mg/L) and chemical oxygen demand (780 to 12,409 mg/L) are found in raw sago factory wastewater effluents [7;11;15;16;17;18;19;20]. Literature reviews stated that sago wastewater contains massive amount of very fine/light suspended matters, protein, ash and fat/lipid contents which demonstrated floating behaviour in nature with specific gravity of nearly 1.0 or less than 1.0 [21;22;23]. Removal of fine suspended particles (< 30 µm) which possesses low settling velocities are impractical by using gravitational sedimentation pond or mechanical filtration methods [24]. These floating or slow settling constituents (such as protein, lipids and carbohydrates), together with volatile matters and fine suspended solids, which are extremely perishable and normally found largely in sago wastewater, are always being overlooked and left out by most of the physical or mechanical treatment systems and subsequently might lead to biofouling/odour problem in place [5;25]. Thus, a research study focused on eliminating total suspended solids (main pollutant parameter) concentration from sago wastewater is imperative.

Past researches reported that suspended organic matters with specific gravity < 1.0 (flotable) are effectively removed by inclined flat plates or arc plate separators [26;27;28;29]. Various plate orientation angles were studied in suspended matters removal, however, gradually increasing angle plate and parabolic-curvilinear movement has not been investigated [30;31;32;33;34;35]. Besides that, flotation technique has been proven to be efficient in treating fine particles as the particle sizes decrease, the surface forces/intermolecular forces would dominate the bulk effects, which enable efficient particle-bubble attachment in water [36].Therefore, the PAF System, embedded with an increasing gradient slope base and aided with air flotation process in this research, is believed to be capable in removing floating/low settling (specific gravity less than or nearly 1.0) suspended matters effectively.

OBJECTIVES OF THE RESEARCH

The objectives of this research are to develop, fabricate and evaluate the performance of a wastewater treatment system by applying parabolic-curved reverse-flow air-flotation concept for the removal of suspended solids from wastewater effluents generated by small to medium-scaled sago factories. This system is embedded with a parabolic-curved plate and equipped with a series of water pump and air curtain installed to induce air/bubbles and to bring suspended solids to the water surface.

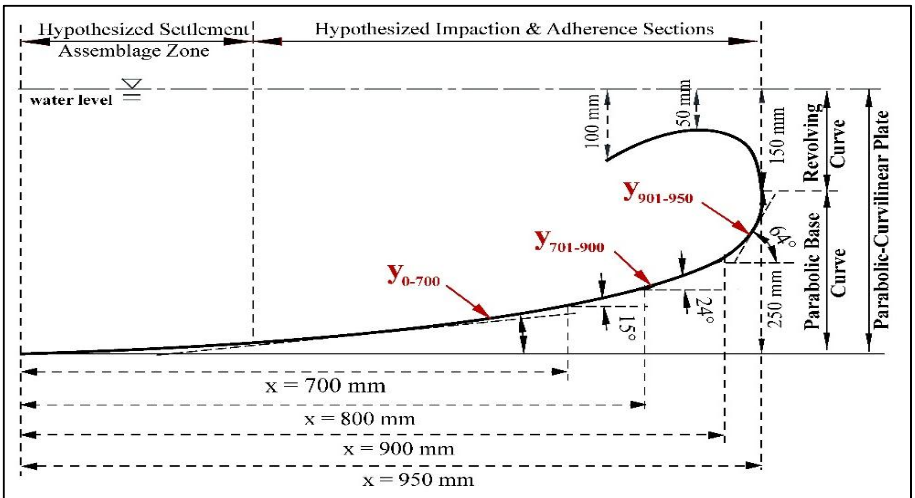
MATERIALS AND METHODS

Preliminary Investigation on Parabolic-Curved Plate Flow

A three dimensional model (Fig 1) is created by using AutoCAD software and analysed by using ANSYS FLUENT R18 simulation software to investigate the fluid dynamics/traces and velocities profiles of the flow in a rectangular tank embedded with a parabolic-curved base plate [37]. Simulations were repeated for several flowrates, i.e., 0.9 L/min, 1.2 L/min, 1.7 L/min, 2.0 L/min and 2.5 L/min. This preliminary model run result is used in developing the PAF system.

Parabolic-Curved Plate

The parabolic flow movement in an increasing curvature manner has become one of the unique characteristic of the flow pattern in this research. The parabolic-curved plate, formed of a parabolic base curve and a revolving curve (Fig 1) and designed in gradually increasing sloping degrees (3º to 64º) (Fig 1), would enhance the uplift motion of suspended solids while travelling along the plate. This curve plane (Fig 1) could promote collision of suspended solids onto the plate and at the meantime guide and lay back the heavier/settled suspended solids towards the lowest elevation zone where the flow movements are less active (as hypothesized by flow simulation results) in the descending slope direction. The parabolic-curved plane is promoting an uplifting motion (Fig 2) which opposes the gravity force and reduces the velocity of the particle's movement due to the dissipation of kinetic energy into potential energy. As a result of reduction in velocity, it prolongs the residence time of suspended solids in the system and indirectly enhances the attachment rate of air bubbles onto suspended solids/flocs.



$$y_{0-700} = 0.00000000012x^4 - 0.000000084x^3 + 0.0001063447x^2 + 0.03010372x + 0.01136364$$
$$y_{701-900} = 0.000797x^2 - 0.913573x + 320.774436$$
$$y_{901-950} = 1327.43\ln(x) - 8858.66$$

Figure 1: Curvature of the Parabolic-Curved Plate

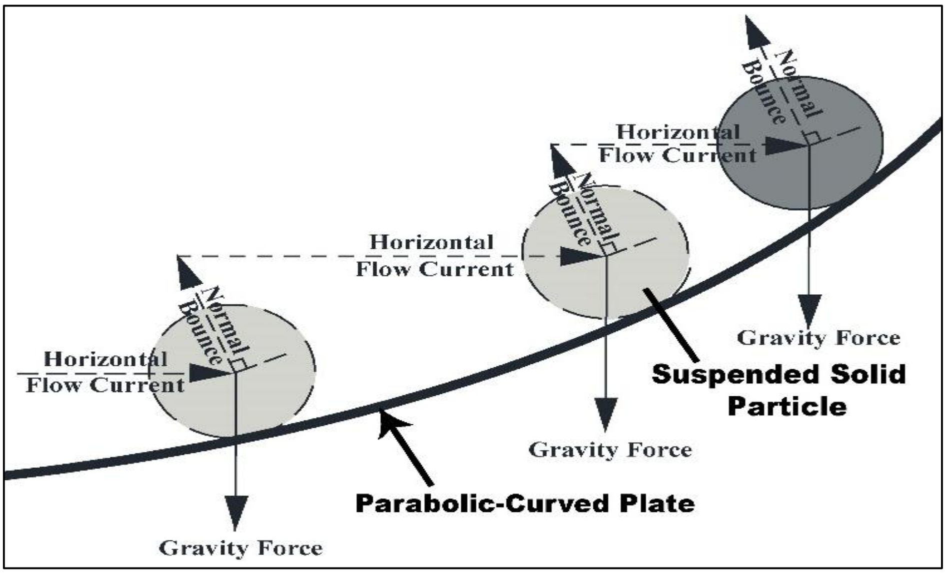


Figure 2: Uplifting Force Resulted by Horizontal Flow Current and Perpendicular (Normal) Bounce of Solid Particle along a Curved Path

Setting up of PAF System

The PAF system (Fig 3 and Fig 4), comprises of a rectangular stainless steel tank, baffle plates, a collection weir, a parabolic-curved plate, a blower, couples of valve-froth collection plates, a series of water pumps and air curtain arranged as in Fig 1, is fabricated for a series of performance testing. Waters flow via the inlet pipe (Fig 3) into the PAF tank in horizontal direction. The parabolic-curved plate is installed in gradually increasing sloping degrees where the end (revolving) section of the parabolic-curved plate reverses the effluents where the effluents are drawn by the water pump series and pumped back into the active treatment zone for repeated bubbling treatment process (Fig 1). Installation of water pump series (eight units in a series) (Fig 3) would enable attachment of bubbles and light-weighted/fine/floatable organic suspended matters until the particle-bubble agglomerates are light enough to float to water surface. Repeated bubbling treatment operations shall maximize the frequency of agitation and collision of suspended solids onto bubble surfaces thus encourage more air-solid attachment.The pumps series is installed in 30° downward diffusions direction to repel the horizontal flow current with an aim to decelerate the solid particles velocity from moving forward in addition to prolong the bubble-particle contact time in the effective treatment zone. Flow in the assemblage zone (lowest elevation) along the parabolic-curved plate is more stable with less active flow movement which would minimize re-suspension of settled solids/sludge as it is located beyond the bubbling area (Fig 1).

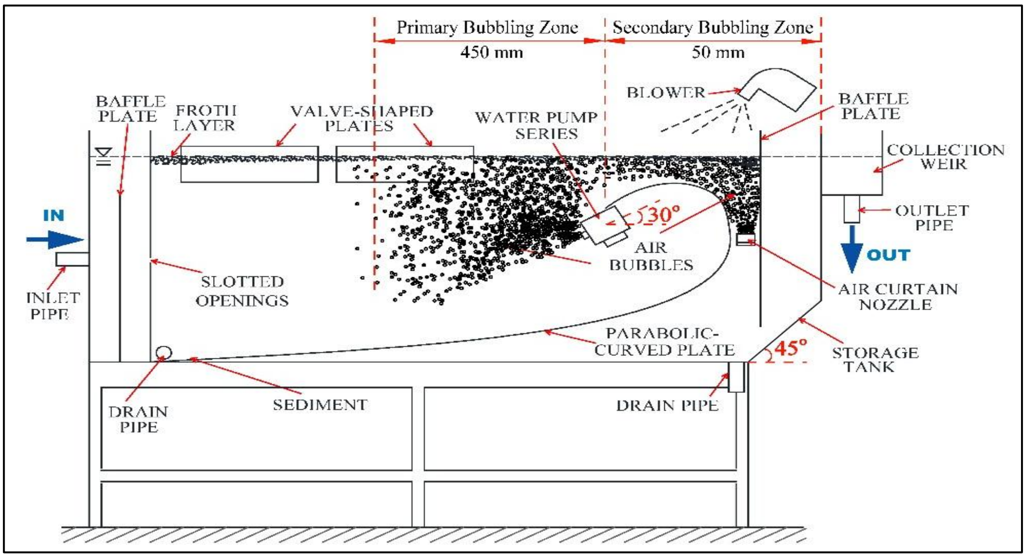


Figure 3: Section View of PAF System

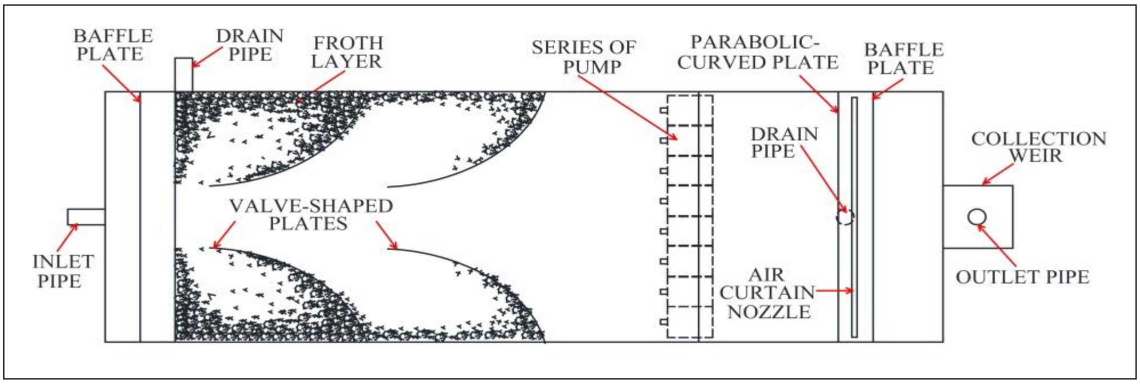
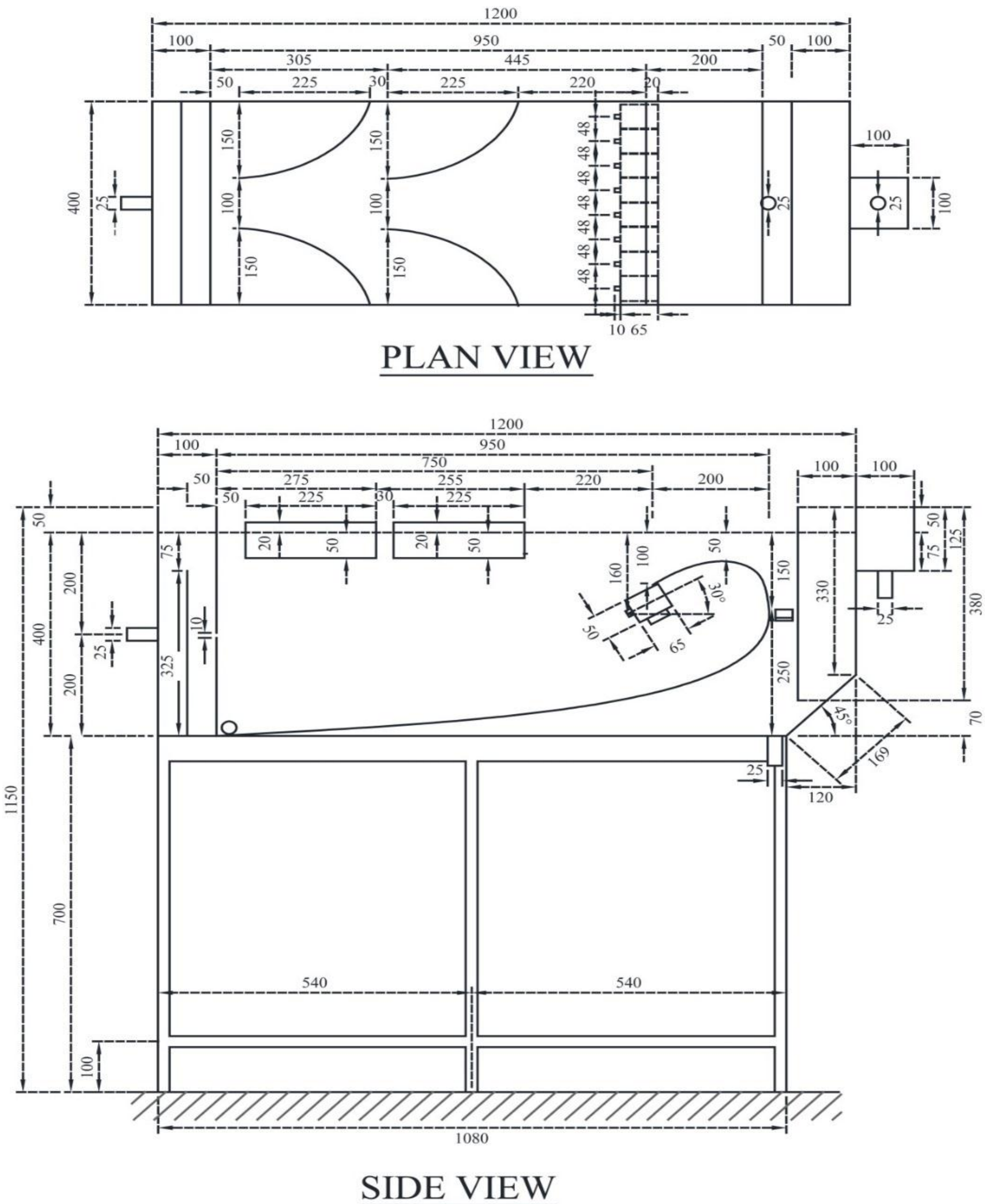


Figure 4: Plan View of PAF System



** All dimensions are in SI unit mm*

Figure 5: Detailed Dimensions and Arrangements of PAF System Components

The accumulated floating bubble-particle agglomerates would form layers of froth which would be steered by a blower (Fig 3) towards the static corner on the water surface (Fig 4) for further manual skimming process. Two couples of symmetrical valve-froth collection plates are installed half-submerged to prevent backflowing of froth layers (Fig 4). The air curtain acted as a secondary bubbling treatment device for subsequent bubble-particle attachment after passing the primary bubbling treatment (generated by water pump series) zone. The air curtain is placed at the contracted path of flow (Fig 3) to resist the residual suspended solids passage with bubbles plume. Baffle plates are designated prior and after the active treatment zone (both primary and secondary bubbling zones) to retain solid particles in forms of froth layer or sludge (Fig 3), and in the meantime to promote uniform distribution in the system [28;29;38;39]. The 45º gradient baffle base (Fig 3) is designed to hold back residual suspended solids by plate impaction and eventually those solids would reside beneath the parabolic-curved plate. Final effluents would discharge out from the PAF System via an overflow collection weir connected to an outlet pipe (Fig 3). The detailed dimensions and arrangement of the fabricated PAF System is depicted in Fig 5.

EXPERIMENTAL WORKS

Preparation of Synthesized Sago Wastewater

Synthesized sago wastewaters were prepared and used for conducting system performance evaluation. In this research, sago pith was shredded into small flakes and blended with clean water to form slurry. Pre-filtration of coarse particles is essential to stabilize the effluents and aid the subsequent treatment efficiencies [17;40]. Therefore, the fibrous solids or "*hampas*" in the blended slurry were sieved with 1.18 mm laboratory test sieve, leaving non filterable supra-colloidal and lighter settable particles with particle size nearly 1 mm or less in the slurry prior being used as the synthesized sago wastewater in the experiment exercises. For the experiments involved chemical application, the prepared synthesized sago wastewater was added with 100 mg/L Sodium Aluminate and 500 mg/L alum under a total system volume of 192 L. Sodium aluminate solution was added into the tank 30 seconds before adding of alum while these chemicals were continuously being stirred in the storage tank for uniform mixing prior being pumped by a hydraulic pump into the PAF system [41]. The PAF treatment system was operated at flowrates of 2.5 L/min, 2.0 L/min, 1.7 L/min, 1.2 L/min and 0.9 L/min.

Performance Test and Sampling Procedures

The synthesized sago wastewaters (water sample P_A) were pumped via the inlet pipe, passing the primary baffle zone, then escaped into the active treatment zone via the 10 mm slotted openings in horizontal flow direction. After passing the primary bubbling treatment zone, the wastewaters escaped into the secondary bubbling zone via the designed 50 mm cleared path, where water sample P_B was taken. The final system effluents were collected as water sample, P_C. The froth layer accumulated on the water surface within the valve-froth collection plates was skimmed and collected as water sample, P_D (Fig 6). Performance test procedures (Fig 6) were repeated for five (5) flowrates (2.5 L/min, 2.0 L/min, 1.7 L/min, 1.2 L/min and 0.9 L/min) without chemical applications. Effects of air curtain, water pump series and parabolic-curved plate on system removal efficiencies were also tested by eliminating the respective features during the experimental cycles under flowrate of 2.0 L/min. An experiment was also carried out for to determine the effect of chemical application under flowrate of 2.0 L/min.

All water samples were then analysed by using Spectrophotometer DR2400 applying Photmetric 8006 method to determine total suspended solids levels and Thermo Scientific Orion AQUAfast AQ3010 Turbidity Meter which applying ISO7027 compliant Nephelometric Method (90º) for determining the turbidity levels [42;43].

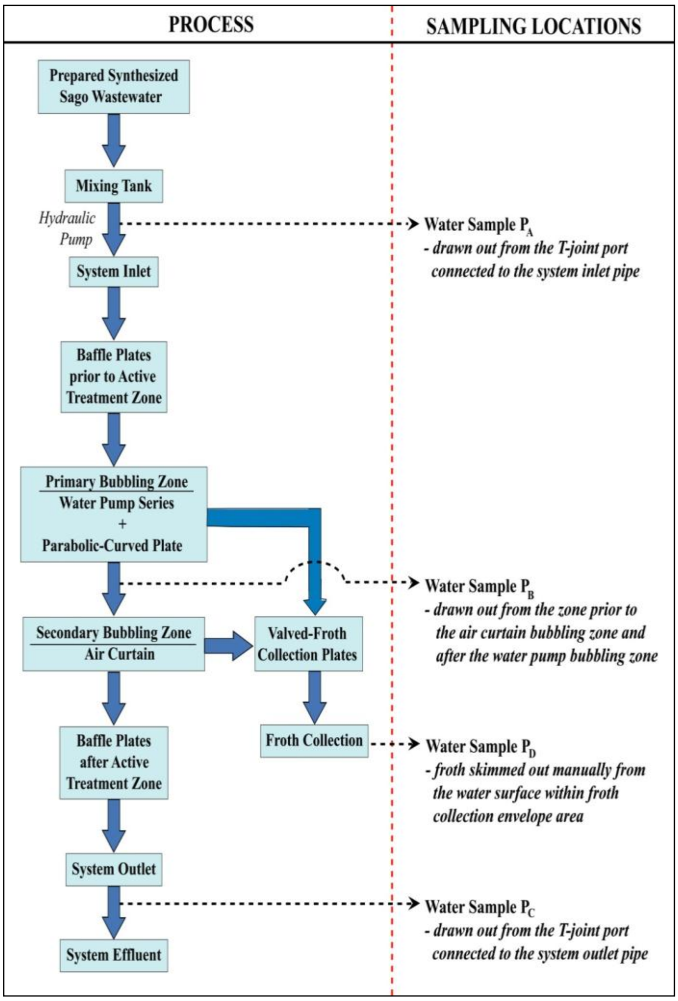


Figure 6: Process Flow of PAF System

RESULTS AND DISCUSSION

Flow Movement Traces and Velocities in a Rectangular Tank Embedded with Parabolic-Curved Base Plate

The axial velocities at the slotted entry prior entering the active treatment zone are calculated as 0.0104 m/s, 0.00833 m/s, 0.00708 m/s, 0.00500 m/s and 0.00375 m/s, for the system flowrates of 0.9 L/min, 1.2 L/min, 1.7 L/min, 2.0 L/min and 2.5 L/min, respectively. The velocities near the entry, the outlet and in the contracted path (air curtain zone) are higher if compared to the velocities (nearly zeroing) at places of i) proximate to the curve surface, ii) within the downstream of parabolic-curved coverage zone and iii) zone below the parabolic-curved plate (Fig 4). Higher velocities at the entry, outlet and contracted zone are most probably due to the decreased passage area under constant flowrate. Besides that, drag caused by the plate under two circumstances, i) the impaction on the gradually increasing slope of the plate, ii) surface friction of the plate, would also retard the flow movement within the parabolic-curved plate zone.

Vector traces results for all the designed flowrates show resemble flow pattern (Fig 7) whereas waters flow horizontally into the tank then elevate gradually while tracking on the parabolic-curved path. Such flow pattern are promoting uplifting motion that resulted during impaction of suspended solids onto the parabolic-curved plate while moving in the horizontal current. Waters after passing the inlet would diverge into upper, intermediate and lower portions (Fig 7). The lower portion of waters guided by the parabolic-curved plate would flow towards the revolving section and then escaped from the curve end into the subsequent stage (air curtain zone) (Fig 7). Therefore, this has hypothesized the placement of water pump series at the end section of revolving curve to create reverse-flow and repeated bubbling treatment process for PAF system. The intermediate portion of waters (Fig 7), after entering the slotted openings, would elevate swiftly and bypassed the revolving section, ultimately arrive at the air curtain zone. With the placement of water pump series nozzling at the opposite direction and creating bubble block to hold back and retain suspended solids for bubble-solids agglomerations, this flow pattern has again hypothesized an enhancement of flow treatment within the tank. For the upper portion of waters, where the waters are moving above the entry level, waters are found swirling up and back towards the entry plate at the first half portion (Fig 7). The uplifting motion could assist in the mechanism of suspended solids flotation and formation of froth layers whilst the backward swirling motion is feasible in establishing a froth collection and accumulation corner. Low-velocity zones, i.e., space beneath the parabolic-curved plate and the lowest elevation of the parabolic-curved slope, are deemed practical to serve as the sedimentation and settlement collection zones (Fig 7). For the simulation (Fig 8) without parabolic-curved plate, erratic random movement and shorter travelled distance are observed. Concomitantly, shorter travelled distance would result in shorter suspended solids residence time whilst erratic random movement and collisions/bounces onto walls/base might aggravate turbulences in the system.

Overall, the parabolic-curvilinear flow pattern (Fig 7) are well-guided by the parabolic curved plate and the design has achieved several treatment enhancement criteria, such as surface froth collection, heavier settlement collection, sedimentation/settlement for residual suspended solids and the potential of reverse-flow and repeated bubbling treatment process, in the tank.

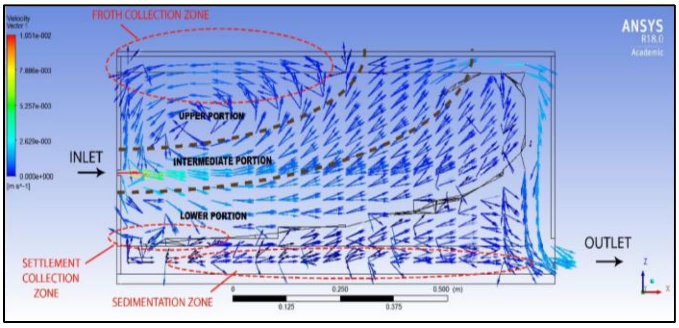


Figure 7: Fluid Dynamics/Traces and Velocities (Q = 2.5 L/min)

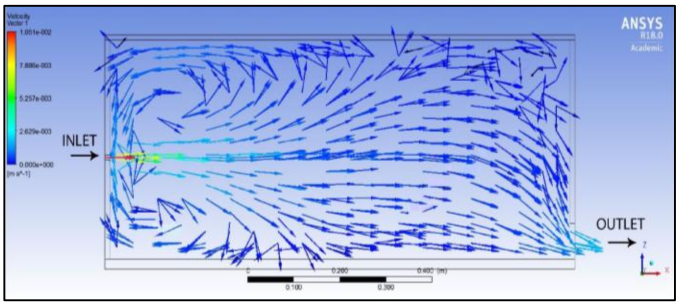


Figure 8: Fluid Dynamics/Traces and Velocities for a System Tank without Embedment of Parabolic-Curved Plate (Q = 2.5 L/min)

Performance of PAF System under Various Flowrates

At the flowrate of 2.0 L/min, the system could achieve approximately 64.18% of turbidity removal and 58.29% of total suspended solids removal (Fig 9 and Fig 10). More than 90% of the total removal efficiencies are contributed by the active treatment zone of P_A to P_B where the pump series, valve-froth collection plates and parabolic-curved plate are encased. Experiment repeated for higher flowrate (2.5 L/min) shows lower removal efficiencies for both turbidity and total suspended solids. The system could achieve better removal percentages under lower flowrates (0.9 L/min, 1.2 L/min and 1.7 L/min) where the results are respectively 81.99%, 66.61% and 77.89% of turbidity removal and 85.63%, 57.78% and 75.97% of total suspended solids removal. Lower flowrates could attain higher removal performance (Ngu, 2009). In this system, it is most probably due to longer detention time allowed more particle-bubble agglomerations and particle-plate collisions mechanisms in the system as the concentration of treatment bubbles within the certain volume of water were increased [44].

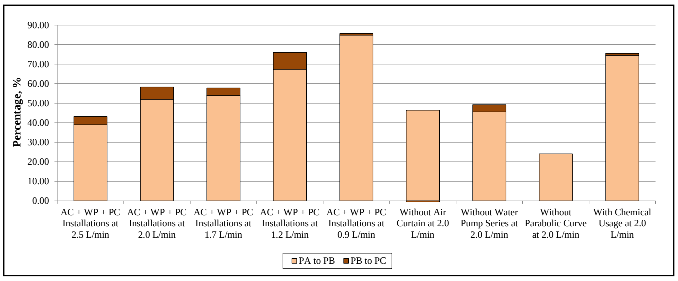


Figure 9: Removal Percentage of Total Suspended Solids in PAF System under Different Experimental Conditions

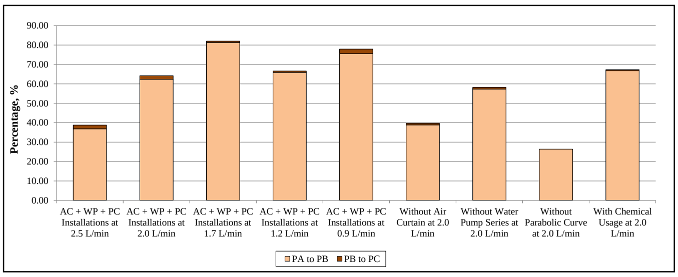


Figure 10: Removal Percentage of Turbidity in PAF System under Different Experimental Conditions

Effect of Chemical Application

Fig 9 and Fig 10 show Aluminium Sulfat and Sodium Aluminate application could raise an additional removal efficiencies of 3.1% of turbidity and 17.2% of total suspended solids. The results prove that chemical application could enhance treatment performance of both active treatment zone and the entire PAF system efficiency. This is most probably due to the presence of chemical has neutralised the charges of colloids and increased the hydrophobicity of suspended solids and thus lead to more bonding and attachment of particles-particles and bubble-particles. Positive effects of chemical application in flotation treatment are supported by various past researches [45;46;47;48;49;50;51].

Air Flotation with Effluents Reverse-Flow and Repeated Bubbling Treatment Process

Water pump series is crucial to generate bubbles for air flotation mechanism as well as to create effluents reverse-flow and repeated bubbling treatment within the system. In the absence of the pump series, the removal performance could be resulted by air curtain bubbling mechanism, impactions and adherence of suspended solids on the parabolic-curved base plate and gravitational settlement of suspended solids due to increased particle's weight. The results in Fig 9 and Fig 10 show that the total removal efficiencies of the system without installation of water pump series have decreased 6.03% of turbidity and 9.04% of total suspended solids if compared to the results of system run with water pump installation, both under flowrate of 2.0 L/min. Air flotation treatment which required bubbling effect to achieve removal of finer suspended solids could hardly be performed without the water pumps operation. The results show that the pump series would enhance the removal performance for the primary treatment zone (P_A to P_B) as well as improve the treatment efficiencies in secondary treatment zone (P_B to P_C) (Fig 9 and Fig 10). This could be due to the floating particle-bubble agglomerates generated by the air curtain are unstable and easily break up while travelling along the long path towards the froth collection corner and suspended solids tend to re-suspend and fall back into the preceding treatment zone. Therefore, continuous bubbles generation by pump series could gradually strengthen, uphold and support the froth layers as more bubbles would attach to the agglomerates until they have reached the ultimate (stable) froth collection corner (Fig 11).

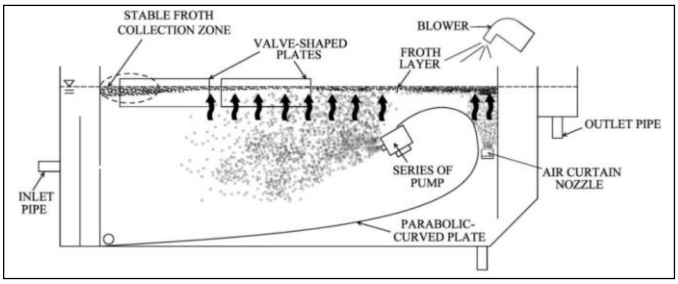


Figure 11L Froths generated from Air Curtain Zone Strengthen, Uphold and Supported by Water Pump Diffusions while Moving towards Froth Collection Corner

Enhancement by Air Curtain

An experiment was carried out by eliminating air curtain from the system under a flowrate of 2.0 L/min. The concentration of turbidity and total suspended solids of the influent are initially 98 NTU and 112 mg/L, respectively, and are reduced to 59.9 NTU (turbidity) and 60 mg/L (total suspended solids) after passing the pump series and parabolic curve treatment zone (primary treatment zone). The final effluents measure 59.1 NTU of turbidity and 62 mg/L of total suspended solids. These results show that the treatment capability of pump series and parabolic-curved plate are > 97% of the total removal efficiencies (Fig 9 and Fig 10). The pollutants levels increased or resulted in negative removal values (-1.79% or -2 mg/L) after passing the primary bubbling zone is most probably due to harbouring of residue suspended solids within the air curtain zone either in form of froth or settlement. A slim layer of suspended solids settlement on top surface of the revolving curve and a layer of froth harboured on the water surface near the edge of the post-baffle wall are observed (Fig 12). Although the removal capabilities of air curtain zone are less than 10% (Fig 9 and Fig 10) of all the total removal efficiencies, it is proven that the air curtain which diffused bubbles plume in counter flow direction could act as a secondary treatment device to agitate and lift the residual suspended solids with bubbles and ultimately enhances the system performance.

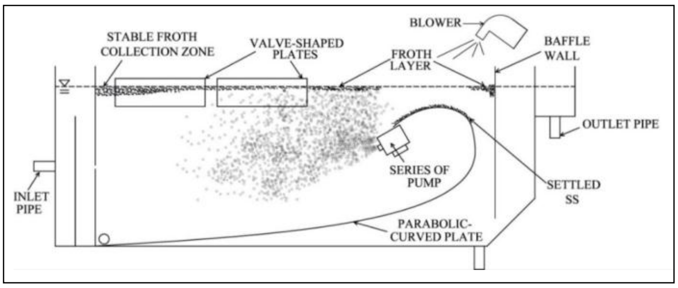


Figure 12: Slim Layer of Settled Suspended Solids Rested on the Top Surface of the Revolving Curve and Froth Accumulated at the Edges and Post-Baffle Wall of Air Curtain Zone

Performance of Parabolic-Curved Plate

The results of an experiment run without the parabolic-curved plate (Fig 13) show that the removal efficiencies are 26.36% for turbidity removal and 24.07% for total suspended solids removal. Without the parabolic-curved plate to restrict and guide the flow towards the pumps' suction zone, large portion of the wastewater may escaped directly towards the system outlet as hypothesized in the flow simulation results (Fig 8 and Fig 13) or bypassed the water pump suction via the upper and lower gaps, resulting lower reverse-flow rate and decreasing the removal efficiency. This is proven when the total removal efficiency run without the parabolic-curved plate significantly drops 34.22% for total suspended solids removal and 37.82% for turbidity removal (Fig 9 and Fig 10) if compared to the system run with parabolic-curved plate. The system is still capable to achieve 45.52% of total suspended solids removal and 57.31% of turbidity removal under solely the performance of parabolic-curved plate (Fig 9 and Fig 10) in primary treatment zone (P_A to P_B). This result emphasizes the treatment capability of parabolic-curved plate in the PAF system.

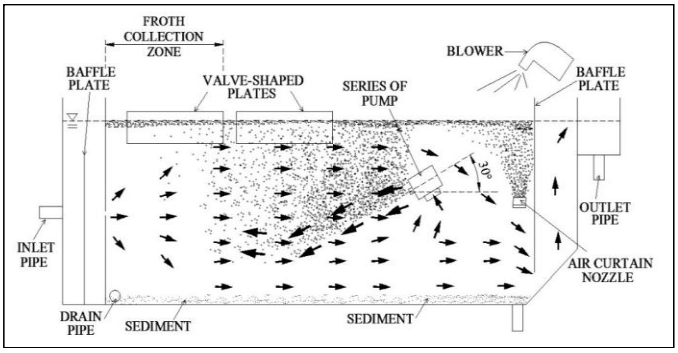


Figure 13: Arrangement of PAF System without Parabolic-Curved Plate Installation

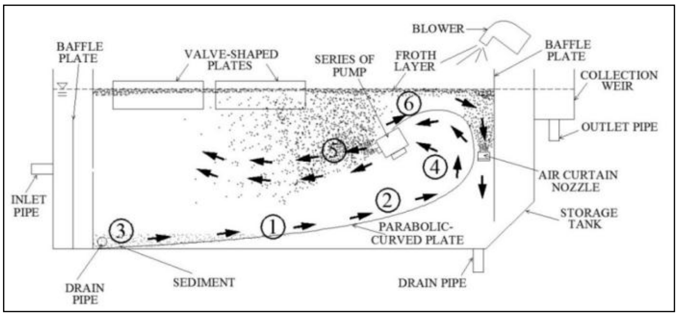


Figure 14: Advantages of Parabolic-Curved Plate

The merits of parabolic-curved plate installation (Fig 14) in the PAF system performance are summarized in the following paragraphs.

1. Under the principles of Conservation of Energy and Bernoulli Equation, while the suspended solids are lifting along the parabolic-curved plate, the increment of potential energy simultaneously reduces the kinetic energy and thus causing the velocity of the suspended solids to decrease. Reduction of velocity inevitably prolonged the suspended solids residence time, which finally enable more occurrence of particle-plate impaction, particle-particle adherence/attachment and particle-bubbles agglomeration.

2. With the installation of parabolic-curved plate, a barrier/impactor was located counter the flow causing mechanisms of particle-plate collision, bouncing and uplifting of suspended solids could take place to hold back the suspended solids in the flow current (Fig 14) [52]. When floatable suspended solids impinge on the curve, they may adhere to each other and thus resulted in larger particles with increased mass, which would subsequently improve their rates of rising.

3. The gradual increasing slope base could relay and retain the settable suspended solids or settlements into the assemblage zone (a valley zone where the flow movement is less active and more stable for sediments

deposition) (Fig 14) created by the parabolic-curved plate slope instead of scattered on the flat tank base (Fig 13) where they might be easily re-suspended and brought along with the forward moving current towards the outlet baffle zone.

4. The parabolic-curved plate has created a revolving zone for guiding the effluents for reverse-flow and repeated bubbling treatment operations (Fig 14).
5. Wastewater with the guidance of parabolic-curved plate would not easily escape/bypass water pump suction zone and also the bubble treatment plumes generated by both the water pump series and the air curtain (Fig 14) if compared with the free moving flow without a parabolic-curved plate (Fig 13).
6. According to the Continuity Equation and Equation of Motion, increase of travel distance would increase the travel time under a constant flowrate. Therefore, the parabolic-curved plate that restricting the flow to move along the curve and subsequently passing the air curtain zone, directly has increased the suspended solids travel path (Fig 14) within the treatment tank and inevitably prolong the residence time for more particle-bubbles attachment and agglomeration occurrence which would led to higher removal efficiencies in the system.

CONCLUSION

The PAF system equipped with a parabolic-curved plate, a water pump series, air curtain and valve-shaped froth collection plates was developed, fabricated and tested experimentally with an aim to study its removal performance of suspended solids from sago factory wastewater effluents. Performance evaluation carried out by using synthesized sago wastewaters shows that the highest achievable removal efficiencies of PAF system are found to be 85.63% (total suspended solids) and 81.99% (turbidity), respectively. More than 90% of the total removal efficiencies are resulted by the primary bubbling zone which involved the execution of parabolic-curved plate and pump series operations. The presence of parabolic-curved plate in the system could improve the removal efficiencies as high as 34.22% for total suspended solids and 37.82% for turbidity. The system performance can further be improved by 13.65% for total suspended solids removal and 24.49% for turbidity removal with the installation of air curtain whilst 9.04% for total suspended solids removals and 6.03% for turbidity removals with the installation of water pumps in the system. Additional 17.2% of total suspended solids and 3.1% of turbidity level removals could be achieved by application of chemicals, i.e., alum and sodium aluminate. This treatment system is deemed to be an effective treatment system for treating wastewater effluents released from sago factories and potentially applicable to other starch production industries.

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