AERATION EFFICIENCY OF A THREE-PHASE FLUIDIZED BED BIOREACTOR DURING FOOD INDUSTRY WASTEWATER TREATMENT

S.V. Manyele*, M.R. Halfani and Y. Benjamin
Chemical & Process Engineering
College of Engineering and Technology
P. O. Box 35131, Dar Es Salaam

The implementation of a three-phase fluidized bed bioreactor (TPFBB) in food-processing wastewater (FPWW) treatment is reported. This study includes the modification of the air distributor (plate design and gas-liquid mixing) for the bioreactor and testing of its aeration efficiency under different liquids. The aeration efficiency for wastewater samples collected from a soft drink processing industry and tannin processing industry (TANWAT) and tap water were compared.

The aeration efficiency parameters studied include bed expansion, air holdup, volumetric oxygen mass transfer coefficient, and alpha factors. The variation of these parameters with air flow rates were studied at different liquid heights, liquid velocity and solids loading. The volumetric oxygen transfer coefficient was observed to range between (140-260 h^{-1}) for tap water, between 120-200 h^{-1} for FPWW and 100-180 h^{-1} for TANWAT wastewater. Higher alpha factors were observed for FPWW (0.85-0.95) than for the case of TANWAT wastewater (< 0.7). The optimum solid loading was established to be 5.0 kg based on the turning point on the variation of the volumetric oxygen transfer coefficient with biomass loading. The modified distributor design has improved the aeration efficiency of the TPFBB

Keywords: *three-phase bioreactor, novel biomass support, distributor design, air holdup, bed expansion, alpha factor*

INTRODUCTION

In Tanzania, the food-processing sector is growing faster and gaining more market, which necessitates development and assessment of wastewater treatment technologies to combat the problems caused by wastewater discharged into public wastewater treatment plants, rivers, lakes and into the Indian Ocean.

Traditionally, food-processing industries are located close to their agricultural sources whereby there is usually one chief raw material that makes up largest percentage of the final food product composition, e.g. sugar manufacture, vegetable and vegetable-oil processing, meat and dairy processing, etc. The exception to this is the beverage sector, in which the product is created from a combination of raw materials. All food-processing plants are water-intensive, leading to large volumes of wastewater.

The FPWW is generally non-toxic and contains fewer hazardous and persistent chemical compounds such as those regulated under the UNEP listing. The wastewater is organic which leads to pollution of receiving water bodies. Such wastewater can be treated by using

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* Corresponding author: E-mail: svmanyele@cpe.udsm.ac.tz; Phone: 255-(0)744-860-944

biological techniques. Part of the problem with the food-processors use and discharge of large volumes of water is that the food processing industries are located in areas where the wastewater treatment plants are not well established, which is true for most Tanzanian cities and towns.

Biological wastewater treatment is the most commonly used form of removing organic compounds in different industrial wastewaters (Cooper and Atkinson, 1981; Cooper, 1995; Fujie *et al.*, 1992; Scott and Ollis, 1995; Halfani, 1998). Despite the low construction costs and high resistance to shock hydraulic loads, conventional biological wastewater treatment methods have a disadvantage of low biodegradation efficiency and longer residence times. These problems have necessitated the use of more advanced technologies, which involve fluidized beds (Halfani and Sokol, 1998). Reduced reactor size leads to reduced land requirements so that such unit can be installed a ready existing land limiting industry compared to 1-4 hectares for facultative ponds.

The TPFBB is a new technology for high efficiency COD/BOD removal in industrial wastewater (Manyele, 1996). In the gas-liquid-solid fluidized bed, solid particles are fluidized by the co-current upward flow of the liquid and a gas. The liquid forms the continuous phase and the gas, a dispersed bubble phase. Minimum fluidization occurs when the mean density of the fluids due to the upward flow of gas and liquid decreases to allow the particles to sink into the liquid-gas mixture, when light particles (like the KMT®) are used. Under normal operating conditions of the TPFBB, a wide range of gas and liquid flow rates can be attained with solids in mixed regime.

The three-phase fluidized bed bioreactor comprises support particles as solid phase, wastewater as liquid phase and air as the gas phase and source of oxygen (for economic reasons). This necessitates intensive considerations on the gas distributor design, which governs oxygen transfer rate in the bioreactor.

Researchers have used different types of support particles in wastewater treatment, to facilitate the immobilization of microorganism, as compared to suspended-culture biological reactors, like $CaCO_3$, $BaCO_3$, particles, soda glass ballotini in water (Oguz *et al.*, 1987), sea sand and Kieselguhr in water (Chapman *et al.*, 1981). Most FBB reported in literature use particles with densities ranging from 1050 to 2800 kg/m^3 (Nore *et al.*, 1992). This study uses light particles (850 kg/m^3), so that only aeration causes fluidization of the bed. Other studies utilizing light particles include Tang and Fan (1990). Such studies were conducted in most cases using water, results of which differ from industrial wastewater, necessitating detailed studies. Figure 1 shows the picture of the KMT® support particles used in this study.

The aeration of the reactor serves two purposes: to supply oxygen for the microorganism growth and secondly to enhance homogeneity of three phases. The role of the support particles in the bioreactor is to increase the rate of mass transfer by offering a large surface area for mass transfer and also to support microorganisms, which adhere to the surface of the particles forming biological films (biomass).

This study is aimed at testing the aeration efficiency of the three-phase fluidized bed bioreactor (TPFBB) with different industrial wastewater and tap water. This paper focuses on the hydrodynamics of the new and improved aerator or gas-distributor design. In this study, an existing TPFBB industrial wastewater treatment plant was modified. The tasks performed include modification of the gas-liquid distributor and optimization the biomass support loading using the variation of k_La with biomass support loading, M_s.

Table 1: Problems leading to redesign of the TPFBB Distributor

Problem requiring rehabilitation	Changes made
The original wind box and distributor plate were made from aluminium plate, which was corroded after prolonged use.	Stainless steel plate (3 mm thick) was used.
Low number of holes and fraction open area on the distributor in the original design.	Changed the number of orifices, from 250 to 408.
Poor liquid-gas mixing because liquid feeding device was mounted on top of the distributor plate.	Both liquid and gas fed through the bottom of the distributor

METHODOLOGY

Modifications of the Distributor for the TPFBB

The gas distributor maintains uniform flow across the column due to pressure created by forcing the gas and liquid through a restriction plate. The design of the distributor is very important since it affects the hydrodynamics of the three-phase fluidized beds. The main purpose of the distributor is to inject small air bubbles in the column.

The modifications made to the distributor are shown in Figure 2 (new and previous designs). The number of holes was increased from 250 to 408 and not 500 because the number of holes depends on other parameters like pitch type (a triangular pitch was used), pitch distance, and the maximum internal column diameter. The details of the TPFBB design criteria were reported by Manyele, 1997).

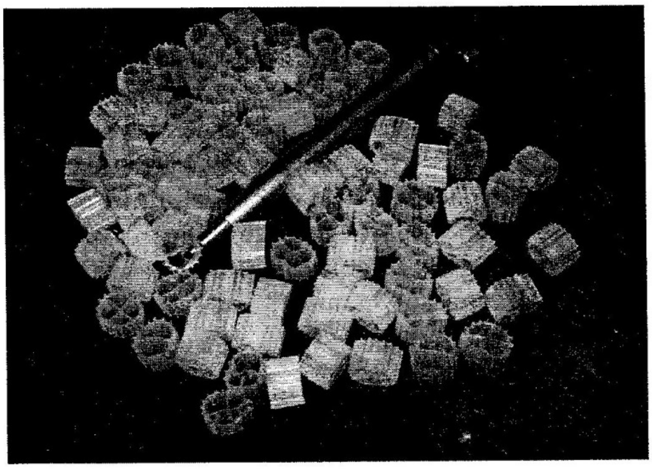
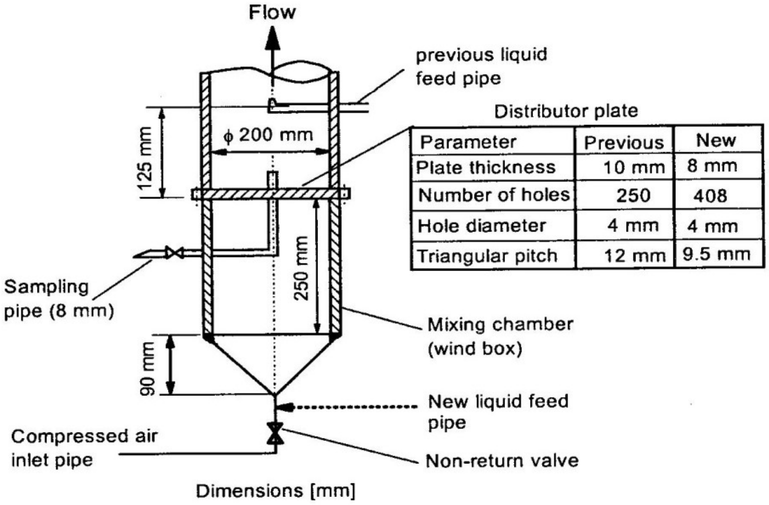


Figure 1: The KMT® support particles

The factors considered during manufacturing include the fact that the plate should: promote uniform and stable three-phase fluidization; it should prevent back flow of liquid during normal operation; and, it should minimize erosion between biomass supports and itself. Structurally, the distributor tray holding the plate should withstand the differential pressure across the plate during normal and abnormal flow of the gas. Also, the plate supports the weight of the reactor contents after shutdown by transmitting the force to the walls of the distributor tray. During start up, the distributor plate should be able to resist thrust that is exerted against the distributor plate as the settled liquid under the plate is carried up into the bed.



Parameter	Previous	New
Plate thickness	10 mm	8 mm
Number of holes	250	408
Hole diameter	4 mm	4 mm
Triangular pitch	12 mm	9.5 mm

Figure 2: Details of the previous and new distributor designs

Experimental Setup

Compressed air was used as the gas-phase in all experiments. Rotameters were used to measure the gas and liquid velocities. The gas superficial velocity was varied from 3 mm/s to 42 mm/s. The KMT® biomass support was used as the solid phase (Manyele *et al.*, 1998; 1997). The liquid flow velocity ranged between 1 and 6 mm/s. Experiments were conducted by determining the bed expansion, air holdup, and the oxygen mass transfer coefficient (Manyele *et al.*, 1997). Figure 3 shows the experimental set-up for the TPFBB (Manyele *et al.*, 1997, 1998).

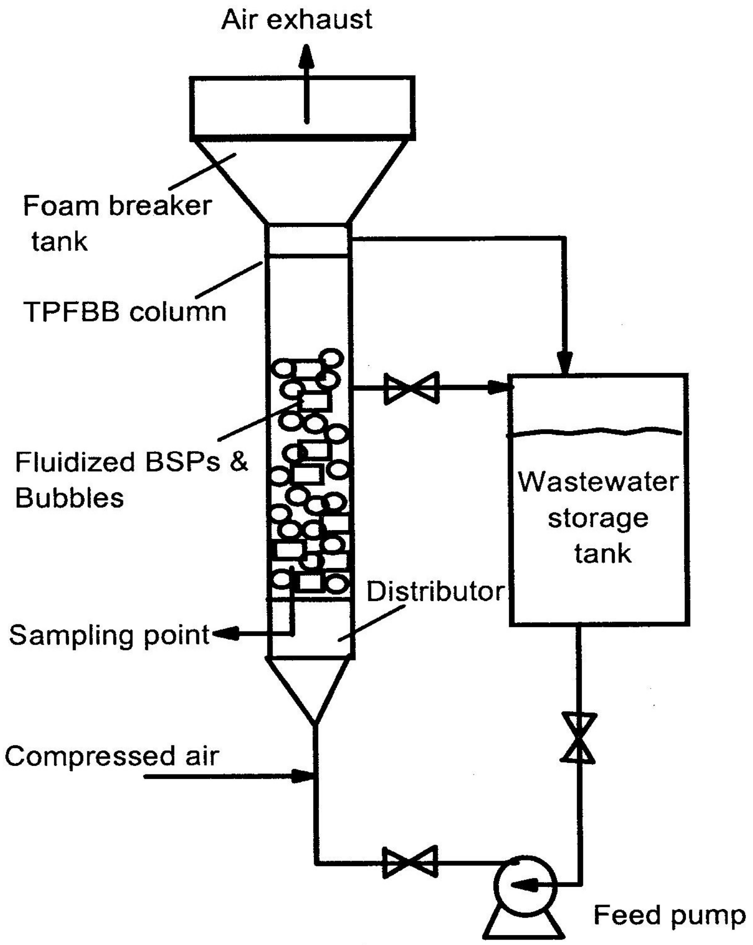


Figure 3: Experimental set up for the TPFBB

The aeration efficiency was studied using different liquids, that is, wastewater samples from a beverage processing plant (denoted as FPWW) and from a tannin extraction plant (denoted as TANNINS) was compared with tap water. The selection of TANNINS was based on the need for testing liquids of different properties in terms of pH i.e. acidic (pH = 3.2 for TANNINS) and alkaline (pH = 11.0 for FPWW) wastewaters compared to the neutral tap water. Moreover, Phase 2 of the project was planned to include TANNINS waste water treatment for COD removal, which necessitates testing the aeration efficiency at the early stage. The details of the experimental facility were also reported by Manyele *et al.* (1997, 1998). Manyele (1997) and Sokol and Halfani (1995.

The hydrodynamic studies conducted include determination of bed expansion, air holdups, and volumetric oxygen mass transfer coefficient, $(k_La)_h$ (Manyele, 1996), at different air velocities, liquid heights, H_L, and for different liquids. The $(k_La)_h$ values were determined using the hydrodynamic method (Manyele *et al.*, 1997), values of which were determined at different liquid velocities in the column and also at zero liquid velocity.

RESULTS AND DISCUSSION

Bed Expansion for Different Liquids

The bed expansion, defined as the ratio of the change in bed height due to aeration to the un-aerated bed height, was determined for different liquids and at different liquid heights for FPWW, TANNINS and tap water, as shown in Figure 4.

Under different operating conditions and different liquids, the TPFBB expanded monotonically with the increase in air velocity. The low matrix density of the support particles attributes this observation, which agrees with former results reported by Manyele *et al.* (1998) and also with the work reported by Bosman *et al.* (1981).

Similarly the bed expansion decreased with the increase in liquid height, which was attributed to

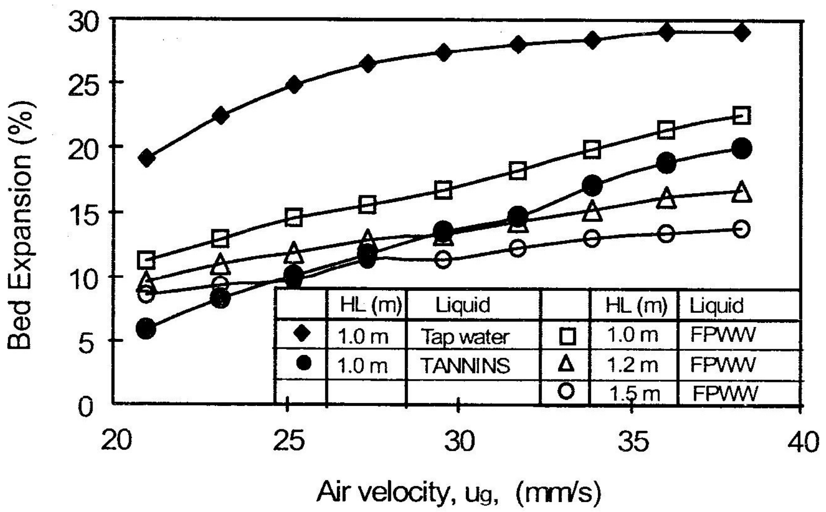


Figure 4: Variation of bed expansion with a Air velocity at different liquid heights for different liquids at zero liquid velocity

the fact that increasing the liquid height increases the hydrostatic head on the gas bubbles emerging from the distributor holes, thus reducing their kinetic energy and agitating effect (Manyele *et al.*, 1998). Moreover, the bed expansion was affected by the nature of the liquid, whereby, lower bed expansion was observed for the TANNINS.

Air Hold-ups for Different Liquids

Air holdup, defined as the volume fraction of total bed occupied by the gas-phase, were also determined for FPWW and compared with other liquids in the bioreactor. Air holdup is an important factor for the biological reactor, as it signifies the extent to which oxygen can be transferred into the liquid phase and ultimately consumed by the microorganisms. Figure 5 shows the values of air holdup at different air velocities, and different liquid heights for tap water and FPWW.

From Figure 5, the air holdup increases with the air velocity but decreases with increasing liquid height. The decrease in air hold up with liquid height was attributed to the fact that increase the liquid height increases the hydrostatic head. Moreover, increasing the liquid height at constant air flow rate contributes to the increase in liquid holdup in the bioreactor, and thus lowering the air holdup. On the other hand, it can be seen that the air holdup values for tap water were higher compared to those of FPWW, due to high viscosity of the FPWW, have higher viscosity than the tap water, and creates stronger resistance towards bed expansion to allow for the higher air holdup during aeration.

Figure 5 shows also that for liquid heights from 1.0 m to 1.5 m, FPWW can be treated at air holdups ranging between 7.5 to 25%. Compared to former studies (Manyele, 1998), where the brewery wastewater samples were treated at air holdup ranging from 4 to 15% only, this study

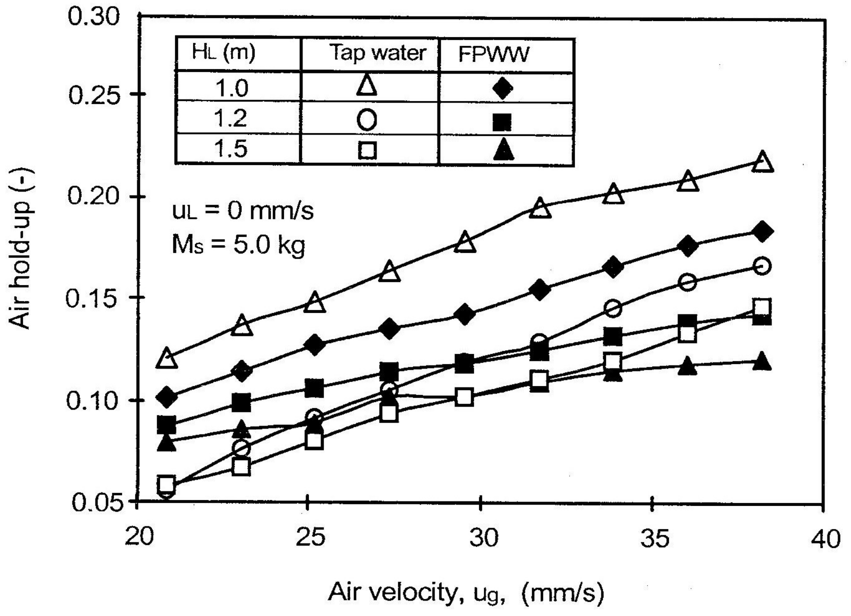


Figure 5: Variation of air hold up with air velocity at different liquid heights at zero liquid velocity for different liquids

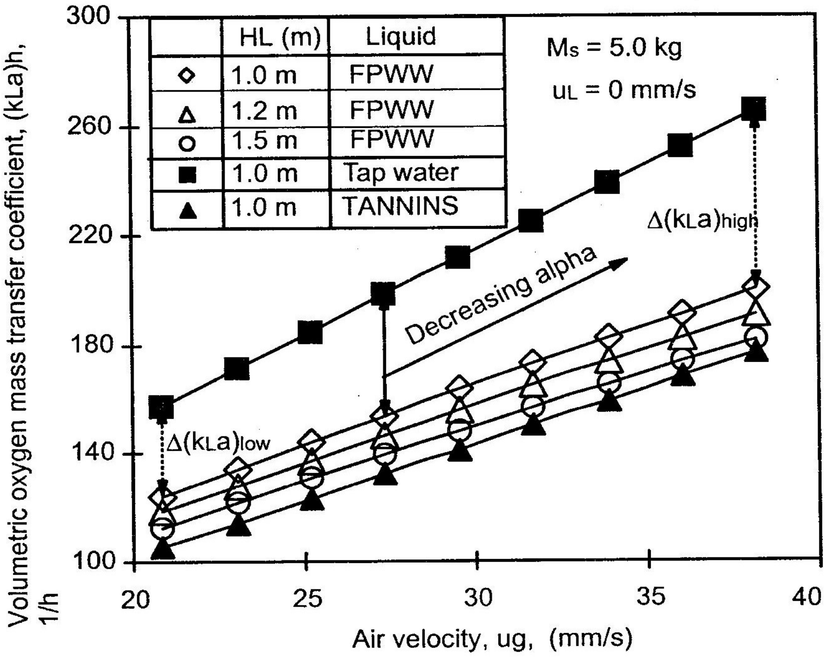


Figure 6: Effect of air velocity on volumetric oxygen mass transfer coefficient at different liquid heights for different liquids

shows that the new distributor design has improved the air holdups in the TPFBB.

Improvement in the Oxygen Mass Transfer Coefficient

The oxygen mass transfer coefficient in the TPFBB was determined using hydrodynamic parameters, as reported by Manyele *et al.* (1997, 1998, 1998b), and Perry and Chilton (1985), denoted here as the hydrodynamic oxygen mass transfer coefficient, $(k_La)_h$. The values of $(k_La)_h$ for FPWW, TANNINS and tap water are shown in Figure 6.

As shown in Figure 6, the hydrodynamic volumetric oxygen mass transfer coefficient increases linearly with air velocity, as reported also by Manyele *et al.*, (1997). This can be attributed to the fact that increasing the air velocity the scoring effect increases, which in turn leads to uniform distribution of the three phases, and into a reduced bubble size, as a result the oxygen transfer rate increases.

Similarly increasing air velocity increases the axial distance traveled by the gas bubbles before breaking, improves the liquid wakes, and increases the turbulence of the eddy movements in the bed, thus increasing the oxygen transfer rate. On the other hand, the hydrodynamic volumetric oxygen mass transfer coefficient was observed to decrease with the increase in liquid height, mainly due to similar reasons which decreases bed expansion and air holdup, that is, because increasing H_L increases the hydrostatic head on the gas bubbles emerging from the distributor hole reducing their kinetic energy, their penetration capacity and their agitation effect.

It can also be observed that the hydrodynamic volumetric oxygen mass transfer coefficient was affected by the liquid viscosity. The higher liquid viscosity corresponds to lower hydrodynamic volumetric oxygen mass transfer coefficient. Tap water has lower viscosity compared to those of tannin and FPWW, thus higher values of $(k_La)_h$ were observed for tap water. The lower values of $(k_La)_h$ for TANNINS can also be attributed to the presence of volatile organic compounds in the wastewater. This is because the volatile compounds exhibit high partial pressure in the bubble's gas phase thus creating more resistance to the oxygen transfer across the film.

The effect of liquid flow rate on $(k_La)_h$ was also studied at three levels (2.6 , 4.0 and 5.3 mm/s) for both tap water and FPWW as shown in Figure 7. Results shows that the liquid flow rate has no significant effect on the k_La values which is in good agreement with the work reported by Chatib *et al.* (1981).

The liquid flow rate has a negative effect on $(k_La)_h$, such that treatment of FPWW must be performed at low liquid flow rates. The results show greater dependence of hydrodynamic volumetric oxygen mass transfer coefficient on the air velocity than liquid velocity. A linear

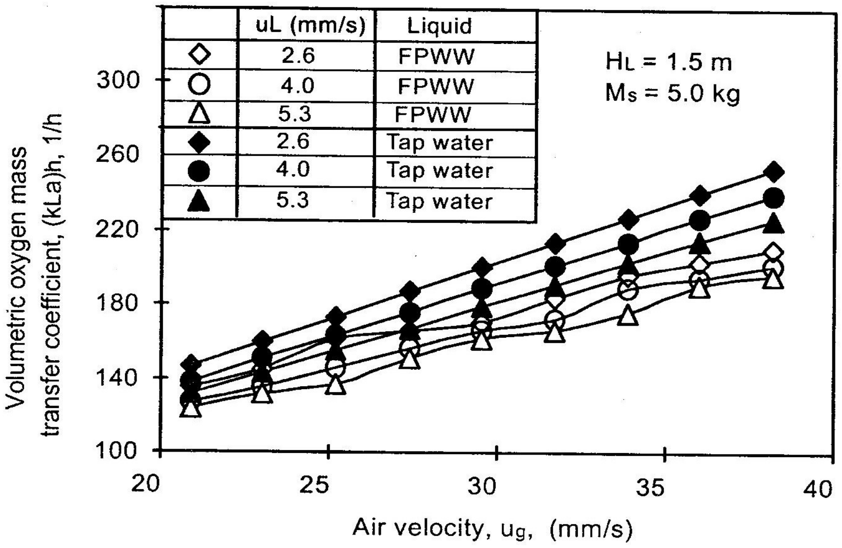
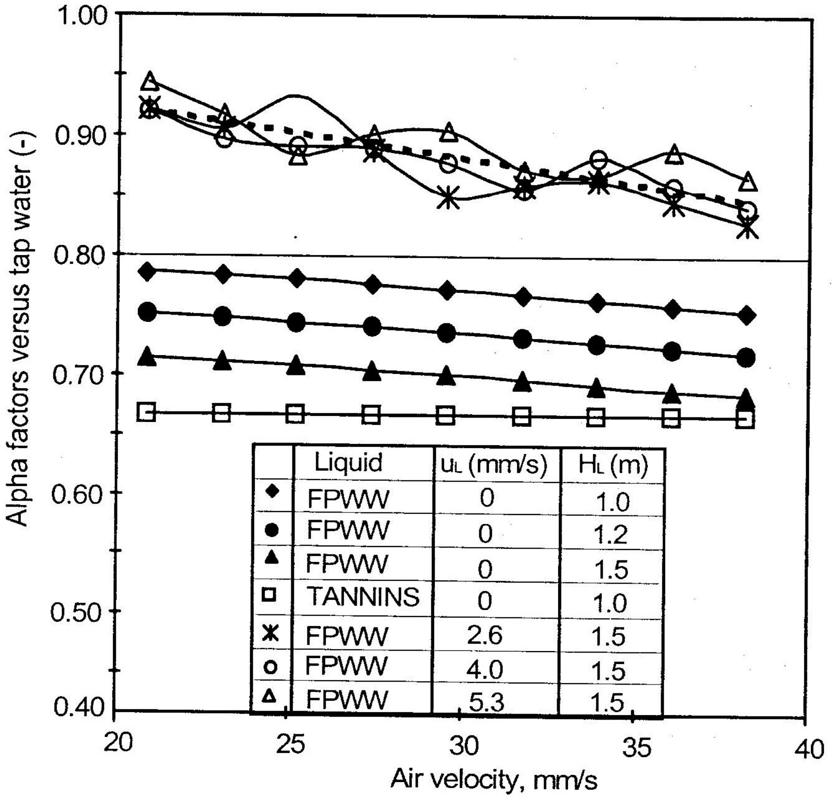


Figure 7: Variation of hydrodynamic oxygen mass transfer coefficient, $(k_La)_h$, with air velocity, u_g, for different liquid velocities for different liquids

relationship between hydrodynamic volumetric oxygen mass transfer coefficient and air velocity was obtained for constant liquid heights (see Figure 6). But it can be seen that the liquid velocity has no significant effect on hydrodynamic volumetric oxygen mass transfer coefficient because there is small separation difference the graphs of different liquid velocities.

The gas-liquid mass transfer rate has been studied for different liquid systems used in biological systems. Components of wastewater that affect $(k_La)_\mathrm{h}$ values include impurities, detergents, phenolics (Manyele, 1996), and fatty acids and fats and greases (FOG), while operational factors observed to affect the $(k_La)_\mathrm{h}$ values include liquid volume or height (as observed also in this study), solid-phase hold up and air flow rate. To compare $(k_La)_\mathrm{h}$ values for different liquids, a parameter called "alpha factor" is used. This is the ratio of $(k_La)_\mathrm{h}$ in wastewater to the $(k_La)_\mathrm{h}$ in clean water (in this case tap water). In this study, alpha factors were determine for FPWW and TANNINS versus tap water at different operating conditions, as shown in Figure 8.

The alpha factor was observed to decrease with increasing air flow rate for all operating conditions. Lower values of alpha were observed at zero liquid



FigFigure 8: Alpha factors at different operating conditions for industrial wastewater aerated under similar

velocity but higher values were observed when the liquid was allowed to circulate at selected flow rates. Also, increasing liquid height at zero velocity was observed to lower the alpha factor for FPWW.

Moreover, it can be seen from Figure 8 that the alpha factor was the smallest and almost constant for the TANNINS compared to FPWW under similar operating conditions. Varying liquid velocity at constant liquid height was observed to have no significant effect on the alpha factor, although the trend was the same (decrease with air velocity) as shown by the dotted line (which shows the average values). Compared with literature, the experimental values of alpha factor after modification of the aerator are higher than in the previous design.

The decrease in alpha values as u_g increases can be attributed to the observation depicted in Figure 6, whereby the difference between the $(k_La)_h$ values between FPWW and tap water is smaller at low air velocities and larger at high air velocities. This is illustrated in Figure 6 for $H_L = 1.0$ m for both tap and FPWW. This implies that at higher air velocity, the ratio between the two values of $(k_La)_h$ will be small.

Effect of Support Mass, MS on hydrodynamic oxygen transfer coefficient, (kLa)$_h$

The $(k_La)_h$ values were observed to increase with solid lading when the latter was increased from $M_s = 1$ kg to 5.0 kg, beyond which the $(k_La)_h$ decreased, as shown in Figure 9. This observation was the same for all liquid heights studied. This observation can be attributed to the increase in solid hold-ups as the solids loading increases which reduces the size of air bubbles and therefore increases the interfacial area.

On the other hand, the decrease in $(k_La)_h$ beyond $M_s = 5.0$ kg was caused by accumulation of support at the top of the bed, which results into poor phase mixing and hence decreasing the $(k_La)_h$ values. This is clearly observed in the Figure 9, whereby, the $(k_La)_h$ value rises to a critical value when the M_s was 5.0 kg for all liquid heights.

Using this behaviour, the optimum solids loading, defined as the solids loading which gives the maximum k_La values, was established to be 5.0 kg for all liquid heights. There is an improvement in the aeration efficiency with new design improvements for the wind box distributor plate because in the previous design the optimum solids loading was determined to be 4.0 kg (Manyele, 1998). Therefore there was an increase in capacity on support particle loading; hence this condition will enhance the mass transfer rate because this provides an additional interfacial area for mass transfer and for biomass support.

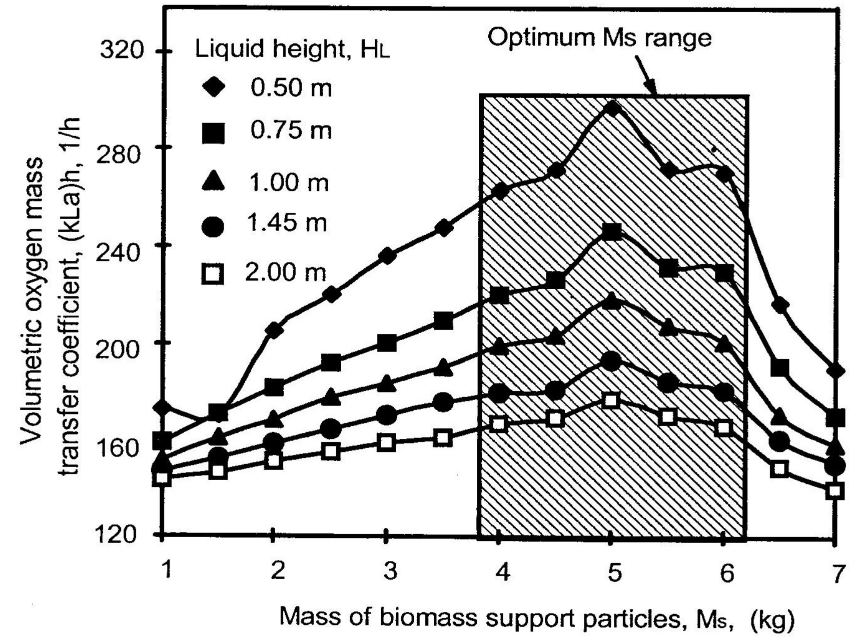


Figure 9: Variation of volumetric oxygen mass transfer coefficient, $(k_La)_h$ with solid loading, M_s at fixed height 2.0 m

Aeration of TANNINS at Optimum Conditions

The aeration of was conducted at optimum conditions to check the effect of aeration on the physical/chemical properties of the TANNINS. The optimum conditions selected for the aeration were: Mass loading, M_s = 5.0 kg; liquid velocity, u_L = 1 - 6 mm/s; liquid height, H_L = 1.0 m; and air velocity, u_g = 20 – 33 mm/s.

During the course of aeration very stable foam was observed. The foam formation in wastewater treatment indicates presence of higher amount of nutrients, in this case large molecular weight proteins. The proteins form stable rigid structure on the surface of the bubble making the latter more stable. Also, the formation of foam in biological wastewater treatment plant indicates nutrients removal. The presence of proteins in the TANNINS can be attributed to proteins lost during processing of the barks of the wattle tree.

This condition is not preferable in wastewater treatment because the foam formed carried the biomass support particles to the extreme top of the column, leaving the fluid phase with lesser support particles. This in turn lowers the $(k_La)_h$. The observed foam could not be contained in the foam breaker tank. Antifoam agents should be used to reduce foaming during wastewater treatment as long as the mass transfer rate is not affected. However, the rate of foaming decreased with time and the foam disappeared after about one hour of aeration. Moe studies are needed to establish the foaming characteristics.

Factors Controlling the Volumetric Oxygen Mass Transfer Rate

There are many factors that will act to hinder the transfer of the oxygen in the FPWW treatment plant. All of these factors must be considered to ensure that sufficient air is added to allow the necessary amount of oxygen per day to be transferred.

The alpha factor in oxygen transfer relates how well oxygen will diffuse into wastewater as compared to clean tap water. This is an important consideration because most aeration equipment is tested and rated in clean water laboratory equipment and these results must be correlated to actual wastewater applications. An alpha factor ranged between 0.65 and 0.95 in this study, indicating that there is still more chance of improvement for use of TPFBB in FPWW treatment.

The bubble size affects the oxygen transfer efficiency. Smaller bubbles produced by the perforated plate at higher air flow rates have more surface area per unit volume. This provides more area through which oxygen can diffuse and thereby increase overall transfer efficiency. Visualize a soccer ball filled with ping pong balls. Both take up the same volume, but the ping pong balls have a much greater cumulative surface area. Also, since fine bubbles provide larger total surface area, they create more friction and rise slower than coarse bubbles. The combination of more transfer area and a greater contact time enhances transfer efficiency. Surface active agents (surfactants), such as detergents originating from washing of the vessels and pipes in the food-industry, lower alpha and the oxygen transfer efficiency. By altering the surface tension, they often cause fine bubbles to coalesce into fewer, larger bubbles. In addition, the thin film of detergent molecules between the air bubble and the wastewater can act as a barrier, increasing resistance to oxygen transfer.

The Novel Biomass Support (KMT®)

The characteristics of biomass support in the biological wastewater treatment vary in terms of size, density and shape. The basis of the three-phase fluidized bed processes is the very large surface area per unit volume of the bioreactor (provided by solids), which is responsible for growth of high-concentration of biomass (Jolly-Voillemin *et al.*, 1996), and also for break-up of gas bubbles to provide large interfacial surface per unit volume, responsible for oxygen transfer into the liquid and finally to microorganisms (Halfani, 1998). Thus, support characteristics are key factors in the performance of the TPFBB. For the KMT® support, the study has been done in detail so far, from which the effect of support mass and the critical support loading (weight of particles charged leading to highest $(k_La)_h$ value) have been established at different operating conditions (liquid height and gas flow rate). The application of the TPFBB can now be introduced in the food processing wastewater treatment.

CONCLUSION

From the above findings, it can be concluded that:

The modified design of the aerator, whereby, both liquid and gas enters the bioreactor via the wind box, has improved the aeration characteristics of the TPFBB, leading to high bed expansion values, high air holdups, high volumetric oxygen mass transfer coefficients and high alpha factors.

The KMT® support is suitable for treatment of food-processing wastewater because it offers high oxygen transfer rates in the biological reactor.

The volumetric oxygen mass transfer coefficient values observed during FPWW treatment are slightly less than those for tap but high enough to support biological life in the TPFBB.

The optimum solids loading into the bioreactor was found to be 5.0 kg, higher than the previous value of 4.0 kg reported by Manyele (1998).

Aeration of TANNINS was accompanied by very strong foaming which lasted for 1 hour, but strong enough to necessitate special attention during wastewater treatment.

It is recommended to transfer the TPFBB technology to the food-processing industries so as to safeguard the environment and save the industries from non-compliances of the standards for effluent discharge.

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SYMBOLS

H_L	liquid height in the column (m)
$(k_La)_h$	hydrodynamic volumetric oxygen mass transfer coefficient (1/h)
M_s	Mass of biomass support particles (kg)
u_g	air velocity (mm/s)
u_L	liquid velocity (m/s)

ABBREVIATIONS

COD	Chemical Oxygen Demand (mg/l)
BOD (mg/l)	Biological Oxygen Demand
TPFBB	Three-Phase Fluidized Bed Bioreactor
FPWW	Food Processing Wastewater
FOG	Fats and grease in wastewater
KMT®	Registered trade mark for the biomass support particles
WWT	waste water treatment

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