Uhandisi Journal Vol. 21 No. 3, December 1997 pp.50-68

PERFORMANCE OF A FLUIDISED BED BIOREACTOR WITH A NOVEL BIOMASS SUPPORT IN TREATMENT OF BREWERY AND REFINERY WASTEWATERS

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ABSTRACT

A removal of COD in brewery and refinery wastewaters in a fluidised bed bioreactor with the KMT^R *biomass support was investigated. It was found that the performance of the bioreactor depended on whether, or not, the mineral salts (nutrients) were added to the wastewaters before the treatment. In treatment of the 'raw' wastewaters (not nutrients were added), the removal of COD equal to approximately 70 and 50% was achieved for brewery and refinery wastewaters, respectively. When the wastewaters were enriched with the nutrients, the COD removal increased to 90 and 85%, respectively. These were obtained when the bioreactor was operated at a ratio of bed volume to bioreactor volume* $(V_b/V_R)_m = 0.55$*, air velocity* $U_m = 0.18$ *m/s, pH = 6.5 - 7.1 and temperature 28 -30°C.*

Stratification of the KMT^R *particles coated with the biomass lead to movement of the bioparticles to the base of the bioreactor where substrate concentration was the highest. This was desirable since the substrate could penetrate far into the biofilm and hence, most of the biomass was active.*

INTRODUCTION

A fluidised bed biofilm reactor, or a fluidised bed bioreactor (FBB), is a novel biological process. It exhibits properties that make it preferable to suspended-cell systems for many continuous bioprocess applications. These properties include extremely high cell concentrations, enhanced cell retention due to cell immobilisation and an increased resistance to the detriment effects of toxic shock loadings [1,2].

Wastewater to be treated is pumped upward through a bed of media at velocities sufficient to induce fluidization of the media (Fig. 1). Once fluidized, each particle provides a large surface area for biofilm formation and growth. The particles eventually become covered with biofilm and the vast available growth support surface afforded by the media results in a biomass concentration approximately an order of magnitude greater than that maintained in a suspended growth system [3,4]. As the biofilms cover the media, the overall density of the biofilm-coated media (referred hereafter to as bioparticles) decreases, which eventually would cause the wash-out of the bioparticles from the bioreactor. This can be prevented by controlling the expanded bed height at a given level *via* intentional wasting of the overgrown bioparticles. Usually a mechanical device is used to separate the biomass from the wasted bioparticles. The cleaned media are returned to the bioreactor whereas the separated biomass is wasted as the excess sludge. In most cases, recycle of bioreactor effluent is employed to ensure uniform fluidization and adequate substrate loading rate.

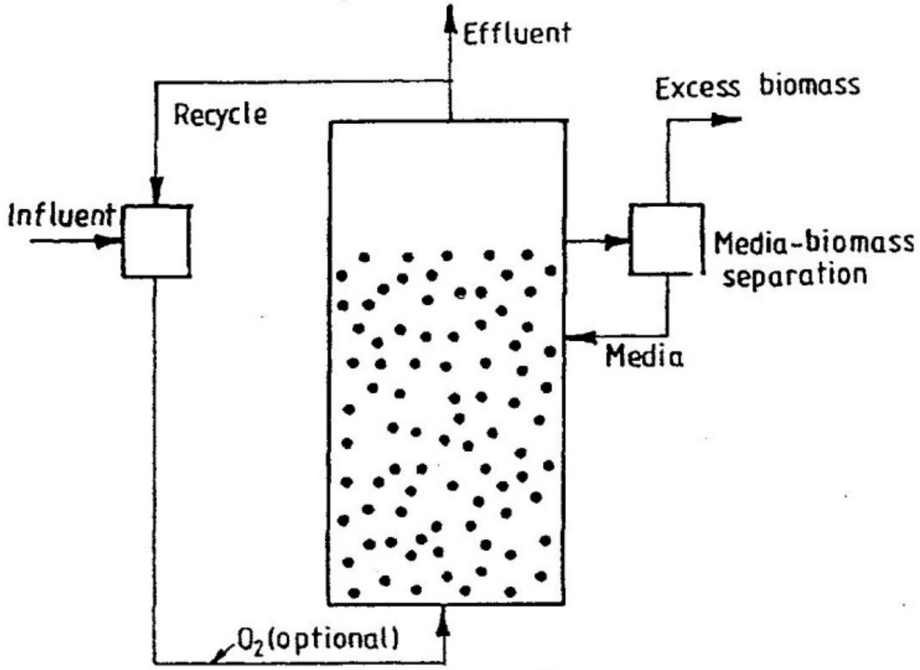

Fig. 1 Schematic diagram of a fluidized bed bioreactor

The FBB is attracting considerable interest as an alternative to the conventional suspended growth and fixed-film processes in a wide variety of wastewater treatment applications. The superior performance of the FBB stems from the following factors [2]:

1. Very high biomass concentration up to 30 - 40 kg/m^3 can be achieved due to immobilisation of cells onto or into the solid particles;

2.The limit on the operating liquid flow rates imposed by the microbial maximum specific growth rate, as encountered in the continuous stirred-tank bioreactor, is eliminated due to the decoupling of the residence time of the liquid phase and of the growth of microbial cells;

3. Intimate contact between the liquid phase and solid phase is achieved;

4. The use of supporting particles allows the partial replenishment of the fluidised bed without interrupting the operation in order to maintain high microbial activity.

A comparison of the FBB with competing biological wastewater treatment processes in municipal applications, in terms of specific surface area, biomass concentration and process loading rate, is summarized in Table 1. As can be seen in the table, the FBB outperforms other bioreactor configurations used in wastewater treatment such as the activated sludge system and packed-bed (or trickling-filter) bioreactor. The use of small, fluidized media enables the FBB to retain high biomass concentrations and thereby operate at significantly reduced hydraulic retention times. Jeris et al. [8] have reported volatile solids concentrations between 30 and 40 kg/m^3 for pilot-scale denitrification studies employing FBBs. As a result, 99% of influent nitrates was removed at empty bed hydraulic retention times as low as 6 minutes.

Fluidization also overcomes operating problems such as bed clogging and the high pressure drop which would occur if small, high surface area media were employed in packed bed operation. A further advantage is the possible elimination of the secondary clarifier, although this must be weighed against the medium-biomass separator.

FBBs have been investigated, at least to pilot scale, for all of the basic secondary and tertiary treatment processes, including carbon oxidation [9], nitrification and denitrification [10], and anaerobic treatment [11], for a variety of waters and municipal and industrial wastewaters.

Sokol and Halfani [5] have analyzed the performance of an FBB with various biomass supports and concluded that a bioreactor with the KMT^R (Kaldnes Miljotechnologi AS) particles has high potential for the application in high-rate aerobic treatment of industrial and municipal wastewaters. A bioreactor with the KMT^{R} biomass support was particularly recommended for treatment of highly toxic industrial wastewaters.

Table 1 Comparison of a FBB with competing biological wastewater treatment processes in municipal applications [3]

Treatment process		Parameter
	(1)	Specific surface area of media (m^2/m^3 bioreactor volume)
Trickling filter		12 - 30
Rotating biological contactor		40 - 50
FBB		800 - 1,200
	(2)	Biomass concentration (kg/m^3)[a]
Pure oxygen activated sludge		3 - 5
Conventional activated sludge		2 - 3
Nitrification activated sludge		1 - 1.5
FBB (carbon oxidation)		12 - 15
FBB (nitrification)		8 - 12
FBB (denitrification)		30 - 40
	(3)	Process loading rate[b]
Pure oxygen activated sludge		1.2 - 2.4
Conventional activated sludge		0.5 - 1.2
FBB (carbon oxidation)		8.0 - 16

[a] In terms of mixed liquor volatile suspended solids (MLVSS) concentration.

[b] In terms of kg BOD_5 removed per m^3 bioreactor volume per day.

The objective of this research was the investigation of performance of an FBB with the KMT^{R} biomass support in aerobic treatment of wastewaters from the Tanzania Italian Petroleum Refinery (TIPER) and the Tanzania Brewery Limited (TBL), both in Dar es Salaam. In particular, the carbonaceous COD removal was investigated.

EXPERIMENTATION

Experimental Arrangement

Experimental set-up

Experiments were performed in the apparatus shown in Fig. 2. The fluidised bed section *9*, constructed from the Duran glass, had a 20 cm internal diameter and was 6 m high. It was ended by a disengaging cap *10* with 60 cm internal diameter and a height of 80 cm. A growing medium, stored in reservoir *1*, was pumped into the bottom of the bioreactor by a centrifugal pump *5*. Before entering the bed, the liquid was mixed with the air by means of a sprinkler. The air was introduced to the bed through a distributor *7* whose plate had 200 x 4 mm diameter holes on a triangular pitch. The air flow rate was measured with a rotameter *11* and was controlled by a needle valve. The liquid recycle flow rate was measured with a rotameter *4* and was controlled by a ball valve. The temperature control system *2* consisted of a coil with cold water and an electric heater coupled with a contact thermometer. The pH was adjusted by a control system *3*, consisting of a pH-meter and micropumps supplying base or acid as required. Sterile conditions were not maintained, the philosophy being that the experiments shall be performed at the same conditions as a full-scale wastewater treatment plant.

The biomass support were the KMT^R particles whose dimensions are shown in Fig. 3. The particles were made of polypropylene of density 910 kg/m^3. The specific surface area of the support could have been regulated up to approximately 400 m^2/m^3 by using the corresponding volume of the particles.

Feed and microorganisms

A growing medium was the wastewater from either TBL or TIPER. The wastewater was enriched with mineral salts as follows [12] (mg/l): $(NH_4)_2SO_4$ - 500; KH_2PO_4 - 200; $MgCl_2$ - 30; NaCl - 30; $CaCl_2$ - 20; and $FeCl_3$ - 7.

An inoculum was the activated sludge taken from TBL and TIPER.

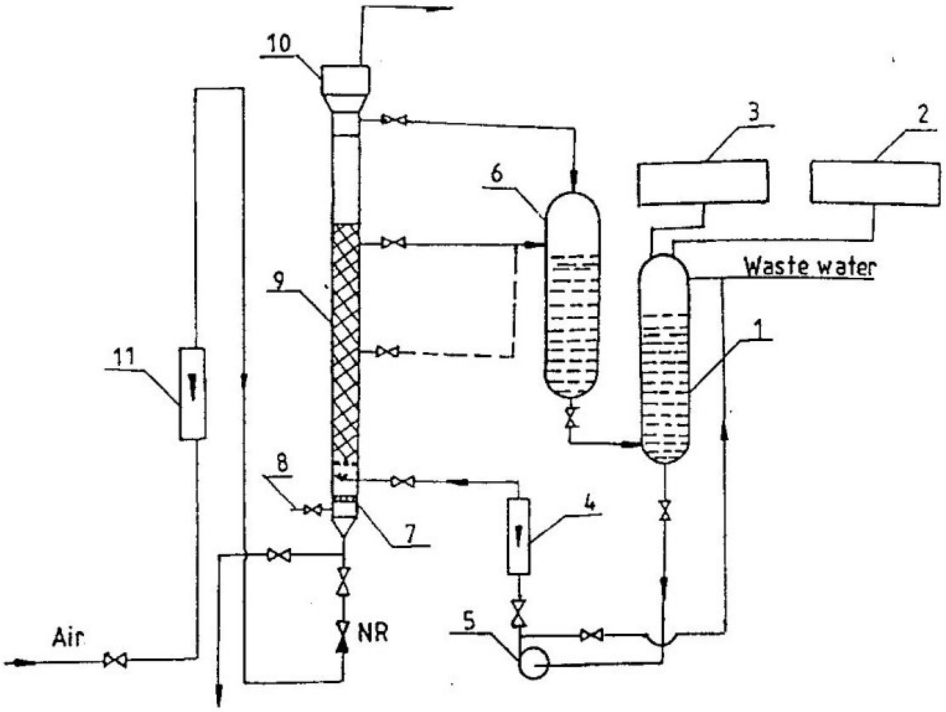

Fig. 2 Schematic diagram of the apparatus

1 - reservoir; 2 - temperature control system; 3 - pH control system;
4 - liquid rotameter; 5 - pump; 6 - intermediate reservoir;
7 - air distributor; 8 - sampling; 9 - fluidised section;
10 - disengaging section; 11 - air rotameter

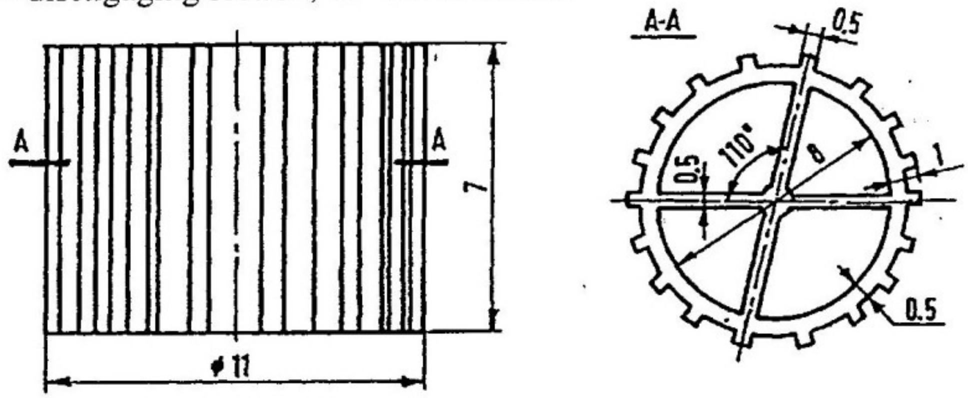

Fig. 3 The KMT^{R} biomass support.

Methodology

Biomass culturing

The continuous culturing of the biomass was carried out at a set air flow rate, following the procedure recommended by Sokol and Halfani [5]. The wastewater, enriched in the mineral salts, was introduced into the bioreactor at a dilution rate of 0.15 h^{-1}. The pH was controlled in the range 6.5 - 7.0 and the temperature was maintained at 28 - 30°C. Measurements of the COD values were conducted when a constant biomass loading on the particles, resulting from the applied air velocity U, has been obtained. This was achieved after operation for approximately two weeks.

Operational range for the bioreactor

Experiments were conducted in a batch operation at constant biomass loading on the particles. The bioreactor was operated in a batch mode, because of its large volume (150 litres); as compared to volume of a laboratory scale bioreactor. If a continuous operation had been applied, large volume of the wastewater would have been required for the operation. However, as it had been established in independent runs, the batch experiments were sufficient to establish the range of the operating parameters at which the largest COD reduction was achieved in the bioreactor.

After achieving the constant biomass loading on the support, the supply of the wastewater and the air was stopped, and the liquid was removed from the bioreactor, leaving the biomass-laden particles inside it. Next, a 'raw' wastewater (no salts were added) was introduced into the bioreactor and the air was supplied at the same flow rate as that at which the biomass had been grown. The samples were withdrawn from the bioreactor in time intervals shown in Figs 4 to 6 and the total COD was determined, following the procedure recommended by Rehm and Reed [13]. The operation was carried out until no further decrease in COD values was recorded.

The experiments were conducted for the ratios (V_b/V_R) equal to 0.45, 0.55 and 0.60. These values of (V_b/V_R) were applied because, as it had been established by Sokol and Halfani [14], the highest values of air holdup, and thus the highest interfacial area, were obtained for these (V_b/V_R). For a given ratio (V_b/V_R), the experiments were conducted for various air velocity U. The experimental results are shown in Figs 4 to 6.

Determination of the optimal operating parameters

In order to establish the ratio $(V_b/V_R)_m$, and the corresponding air velocity U_m, giving the largest COD reduction, experiments were repeated for those values of $(V_b/V_R)_m$ and U_m for which the largest reduction in COD were obtained in the earlier runs (Figs 4 to 6). The

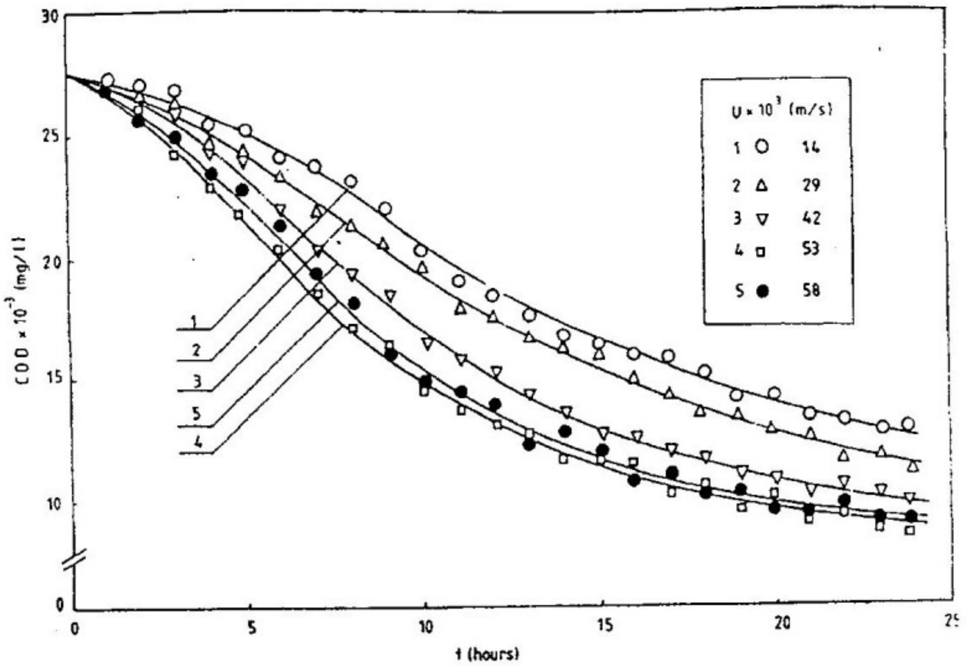

Fig. 4 Dependence of the COD values on time established for treatment of TBL wastewater at various air velocities U and ratio of bed volume to bioreactor volume $(V_b/V_R) = 0.60$. No mineral salts were added to the wastewater before the operation.

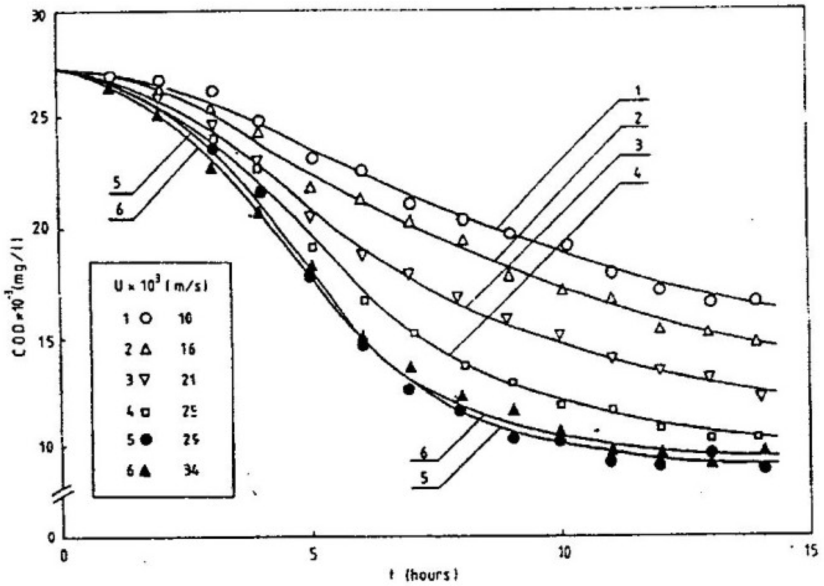

Fig. 5 Dependence of the COD values on time established for treatment of TBL wastewater at various air velocities U and ratio of bed volume to bioreactor volume $(V_b/V_R) = 0.55$. No mineral salts were added to the wastewater before the operation.

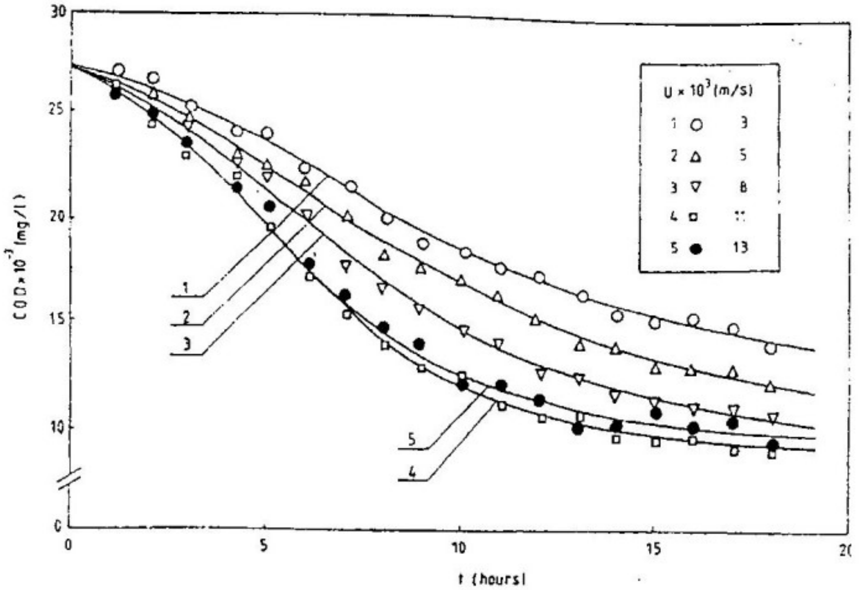

Fig. 6 Dependence of the COD values on time established for treatment of TBL wastewater at various air velocities U and ratio of bed volume to bioreactor volume $(V_b/V_R) = 0.45$. No mineral salts were added to the wastewater before the operation.

experiments were also performed for the ratio $(V_b/V_R) = 0.50$ and the air velocity $U = 0.018$ m/s. This was to cover the searched range of (V_b/V_R), i.e. 0.45 - 0.60, every 0.05 and thus, to establish the value of $(V_b/V_R)_m$ with the accuracy sufficient for industrial practice. The air velocity $U = 0.018$ m/s was obtained from Fig. 9, after reading the value of U for the ratio $(V_b/V_R) = 0.50$.

The experimental results are given in Fig. 8.

Wastewater treatment

Experiments were performed with TBL and TIPER wastewaters enriched with the mineral salts as given earlier. The purpose of these experiments was to investigate the performance of the bioreactor in treatment of wastewaters supplemented with the nutrients.

The experiments were conducted for the ratio $(V_b/V_R)_m = 0.50$ and the air velocity $U_m = 0.018$ m/s which, as had been established, gave the largest COD reduction in the earlier runs. The experimental results are shown in Figs 10 and 11.

In order to find out whether, or not, the amount of the nutrients was sufficient for biomass growth, the experiments were also performed with

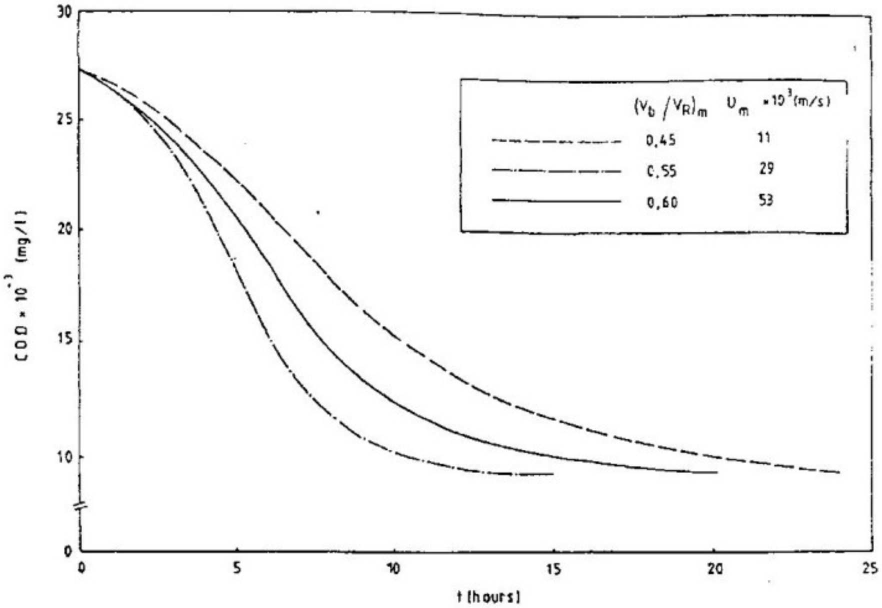

Fig. 7 Comparison of the COD reduction for a treatment of TBL wastewater obtained at various ratios $(V_b/V_R)_m$ and the corresponding air velocities U_m.

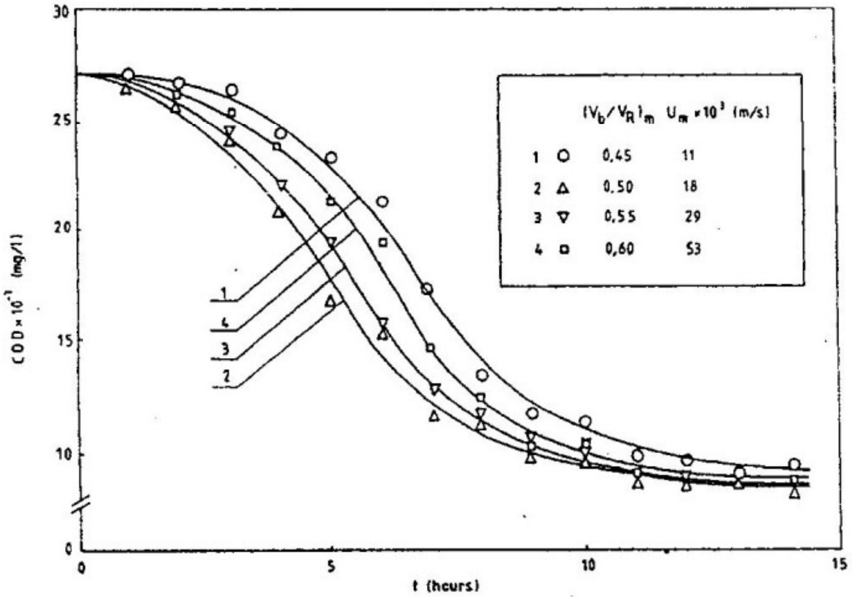

Fig. 8 Dependence of the COD values on time obtained for treatment of TBL wastewater at various ratios $(V_b/V_R)_m$ and the corresponding air velocity U_m.

the wastewater enriched in a double amount of the salts. The results are given in Figs 10 and 11.

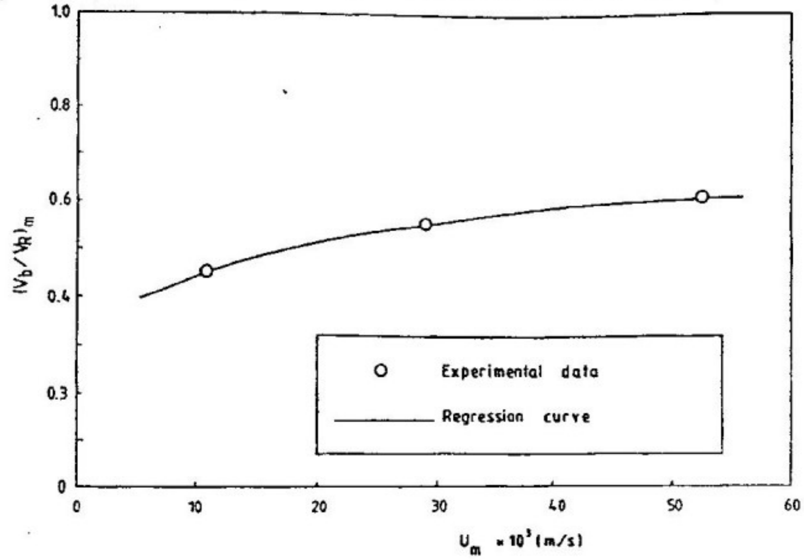

Fig. 9 Relation between the ratio $(V_b/V_R)_m$ and the corresponding air velocity U_m.

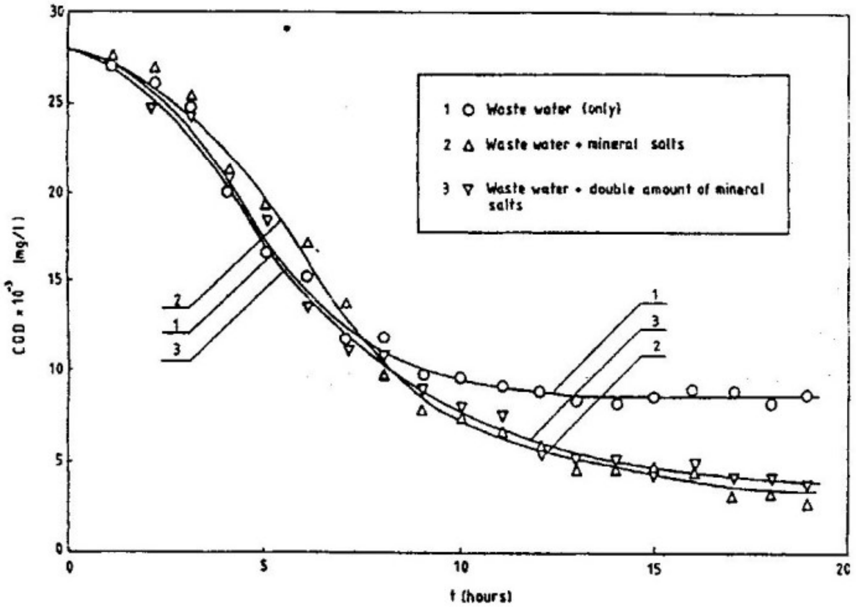

Fig. 10 Dependence of the COD values on time obtained for a treatment of TBL wastewater for various preparation of the wastewater before the operation.

RESULTS AND DISCUSSION

Analysis of the operating parameters

It can be seen in Figs 4 to 6 that for a given ratio (V_b/V_R), COD removal depended on time of the operation and air velocity U. As can be noted in Fig. 4, the rate of COD reduction initially increased monotonically with an increase in the U and then decreased, attaining the largest value at U_m

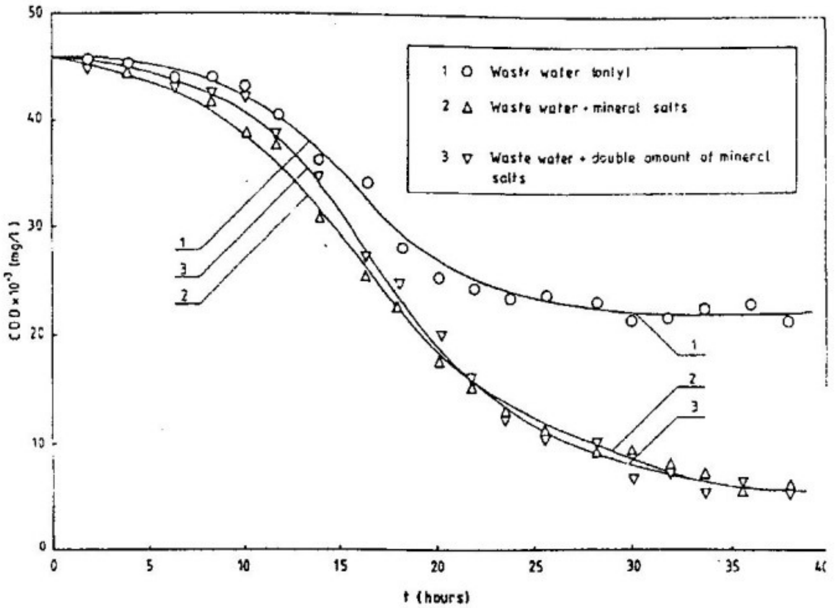

Fig. 11 Dependence of the COD values on time established for treatment of TIPER wastewater for various preparation of the wastewater before the operation.

= 0.053 m/s. This can be explained by the fact that with an increase in air velocity, external (air - liquid) oxygen transfer increased and consequently, the amount of the oxygen supplied for biomass growth was increased. For the air velocity U smaller that 0.053 m/s, the oxygen was the limiting factor for biomass growth. It can be noticed in Fig. 4 that an increase in the air velocity U above 0.053 m/s had no affect on the rate of COD removal. Thus, for the air velocities greater than 0.053 m/s, factors other than oxygen transfer were controlling the rate of COD removal.

It can be noted in Figs 4 to 6 that the air velocity U_m, at which the largest decrease in COD had been obtained, depended on the ratio (V_b/V_R) and hence, on the corresponding volume V_b of the support applied in the bioreactor. With the bed volume increasing, the values of U_m increased. Thus, the use of an excess volume of the support will lead to an increase in the amount of the air required for biomass growth and consequently, to an increase in the resulting energy cost, as observed by Wheeldon and Bayley [15].

Comparison of the largest reduction in COD values obtained for ratios $(V_b/V_R)_m$, and the corresponding U_m, is shown in Fig. 7. The figure shows that a reduction in the COD values initially increased with an increase in the ratio $(V_b/V_R)_m$ and then decreased, attaining the largest value at $(V_b/$

V_R) = 0.55. An increase in the COD removal with an increase in the (V_b/V_R), up to the value of 0.55, was due to the fact that for the increasing ratios (V_b/V_R), more biomass grown on the particles participated in the biodegradation. Consequently, the higher rate of the COD removal was observed. A decrease in the rate of COD removal observed with a further increase in the value of (V_b/V_R) can be attributed to the fact that in the latter case, a significant volume of the bioreactor was occupied by the bioparticles and consequently, the aeration characteristics of the bed has worsened [14]. As can be noted in Fig. 7, the highest COD removal and hence, the smallest values of COD at the end of the TBL wastewater treatment, was achieved for the ratio $(V_b/V_R)_m = 0.55$ and the corresponding air velocity $U_m = 0.029$ m/s.

Determination of the optimal operating parameters

As can be seen in Fig. 8, the smallest value of COD at the end of the treatment of TBL wastewaters equal to 8,100 mg/l was achieved for the ratio $(V_b/V_R)_m = 0.50$ and the corresponding air velocity $U_m = 0.018$ m/s. Therefore, these values of (V_b/V_R) and U were considered to be the optimal operating parameters, i.e. giving the largest reduction in the COD values. Subsequently, as mentioned earlier, all the remaining experiments on investigation of the efficiency of the bioreactor in treatment of TBL and TIPER wastewaters were performed for the ratio $(V_b/V_R)_m = 0.50$ and the air velocity $U_m = 0.018$ m/s which has been obtained from Fig. 9.

Wastewater treatment

TBL wastewater

It can be seen in Figs 10 and 11 that the values of COD at the end of the treatment, i.e. when no further reduction in COD was observed, depended on preparation of the wastewater before the operation, viz. whether, or not, the mineral salts were added to the wastewater to be treated. As can be noted in Fig. 10, when a 'raw' TBL wastewater was treated, the values of COD decreased from 26,600 mg/l to 8,300 mg/l, i.e. about 70% COD removal was obtained. A high value of COD after the treatment was owed to the fact that, as has been discussed by Sokol and Halfani [14], there was a deficiency of the nutrients in the wastewaters for microorganims growth. It can be noticed in Fig. 10 that in treatment of TBL wastewaters enriched with the nutrients, the decrease of COD value to about 2,800 mg/l was achieved, i.e. approximately 95% COD reduction was obtained. It was also established that when more nutrients were added to the wastewater before treatment, no improvement in the performance of the bioreactor was obtained. Thus, the amount of the nutrients recommended by Livingston and Chase [12], and used in the experiments, was sufficient for microorganisms growth.

It was visually observed during experimentation that stratification of the particles coated with the biomass led to their movement to the base of the bed where concentration of organic compounds was the highest. This was desirable since the compounds could penetrate far into the biofilm so most of the biomass was active [16,17].

TIPER wastewater

It can be seen in Fig. 11 that in treatment of a 'raw' TIPER wastewater, a decrease of COD value from 46,750 mg/l to 21,600 mg/l, i.e. only 50% COD reduction, was obtained. When the wastewater was enriched with the nutrients, the reduction in COD to 7,100 mg/l, i.e. approximately a 85% COD removal, was achieved. It can be noticed in Fig. 11 that in experiments carried out with a double amount of the nutrients, no improvement in the bioreactor performance was obtained, suggesting that a sufficient amount of the nutrients for biomass growth was used in experiments.

Owing to the long term need for new energy sources, there will be a considerable increase in the environmental impact of waste liquors from coal processing, arising from the coal gasification and liquefaction processes now under development [6]. Amongst the compounds that are the greatest biohazards in coal-derived liquors are phenols, polycyclic organics, thiocynates, ammonia and cyanides.

Performance efficiency of the bioreactor

The performance efficiency *E* of the bioreactor in COD removal, defined as $E = ((COD_0 - COD)/COD_0) \times 100\%$, is shown in Fig. 12. This figure shows that when the wastewaters were supplemented with the salts, the value of *E* increased from 70 to 90% and from 50 to 85% for treatment of TBL and TIPER wastewaters, respectively.

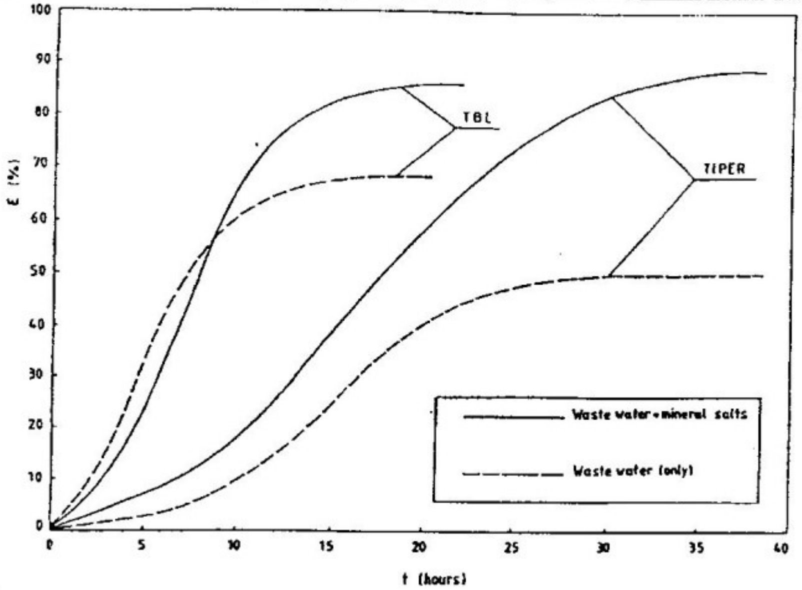

Fig. 12 Efficiency *E* of the bioreactor established for a treatment of TBL and TIPER wastewaters for various preparation of the wastewaters before the operation.

It should be pointed out that, despite the biodegradation of practically all organic matters contained in the TBL wastewater, the bioreactor effluent was not suitable for disposal. This was because concentration of heavy metals (Ca, Cu, and Fe) was higher than that recommended by WHO (World Health Organisation) for industrial effluents [18]. Therefore, a biological degradation of TBL wastewater should be followed by chemical treatment of the effluent in order to conform with the required standard for final effluent.

It should be also mentioned that some compounds contained in the TIPER wastewater, e.g. thiocyanates, cyanides and nitrates, were not degraded during the operation and thus the effluent did not conform with the standards required for phenolic effluents [19]. This was because the bacterial population applied in the process has not been sufficiently adapted to be appropriate for oxidation of these compounds. Since complete degradation of all hazardous compounds present in wastewater is desirable in one process, further experimentation is required to adapt the symbiotic bacterial populations which may effectively degrade also thiocyanates, cyanides, nitrates and ammonia.

CONCLUSION

From experimentation with the fluidised bed bioreactor with the KMT^{R} biomass support, the following conclusion can be drawn:

1. The performance efficiency of the bioreactor with KMT^R support in treatment of brewery and refinery wastewaters depended on the presence of the nutrients in the wastewater to be treated. In treatment of the 'raw' wastewaters, the efficiency of 70 and 50% was achieved, respectively. When wastewaters were enriched in the nutrients, the efficiency increased to 90 and 85%, respectively. These efficiencies were obtained when the bioreactor was operated at the optimal parameters, that is, at a ratio of bed volume to bioreactor volume $(V_b/V_R)_m = 0.55$, air velocity $U_m = 0.018$ m/s, pH = 6.5 - 7.1 and temperature 28 - 30°C.

2. The biodegradation of practically all organic matters contained in TBL wastewater was achieved. However, it is recommended that the biodegradation shall be followed by a chemical treatment of the effluent from the bioreactor in order for the final effluent to conform with the standards recommended for industrial effluents.

3. Stratification of the KMT^R particles coated with the biomass lead to movement of the bioparticles to the base of the bioreactor where substrate concentration was the highest. This was desirable since the substrate could penetrate far into the biofilm and hence, most of the biomass was active.

4. Owing to the long term need for new energy sources, there will be a considerable increase in the environmental impact of waste liquors from coal processing, arising from the coal gasification and liquefaction processes now under development. Amongst the compounds that are the greatest biohazards in coal-derived liquors are phenols, polycyclic organics, thiocynates, ammonia and cyanides.
applications.

NOTATION

E	performance efficiency, %
t	time, h
U	superficial upflow air velocity, m/s
V_b	settled bed volume, m^3
V_R	bioreactor volume, m^3

Subscript

m denotes values giving the optimal COD reduction

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The manuscript was received on 6th September 1997 and accepted for publication, after corrections, on 29th December 1997