ABSTRACT

In recent times, the High Rate Anaerobic Wastewater Treatment has emerged as an effective and economic alternate to the conventional aerobic and anaerobic systems of treating domestic as well as various types of industrial wastewaters. Upflow Anaerobic Filter (UAF), conventionally employing very long solids retention times (SRT > 600 days), obviously falls under this classification. Two important benefits of high SRT systems are reduced required reactor volume and the substantial buffering capacity against shock loadings and toxic or inhibiting constituents in the feed. Obviously, operating a reactor at a high SRT offers a much desired safety factor to protect against a system failure, which is advantageous, particularly in case of biological reactors. The designer, thus, always attempts to maximize the reactor biomass concentration. Young and McCarty (1969)\(^7\), therefore, developed an Upflow Anaerobic Filter (UAF) – a fixed film anaerobic biological reactor, being fed in upflow mode, which retains the microorganisms in the reactor in the form of a biofilm on the supporting media provided for the purpose and as suspended solids trapped in the media pores. Long SRT (>600 days) is obtained without using recycle or solid separation device, making the system operationally simple. In fact, UAF is stable and simple biological reactor requiring no special operational technique to achieve high degree of performance. Maintaining long SRT, irrespective of short hydraulic retention time (HRT), allows the application of high organic loading to the process. Since the pioneering work by Young and McCarty (1969)\(^7\), the application of UAF has extended to the treatment of not only various types of industrial wastewaters with varying strength but also to domestic wastewaters.

At present, Organic Loading Rate (OLR) is the sole design parameter being used to design UAF without considering the influence of either the process kinetics or...
the reactor hydrodynamics, on the overall substrate removal rate. The optimum process performance is, therefore, seldom achieved because of high degree of empiricism, which prevails in the design and operation of UAF. An engineered design and operation of UAF, therefore, requires an understanding and knowledge of process kinetics which is primarily influenced by hydrodynamic behavior of the reactor i.e. whether the reactor follows an ideal plug flow, or complete mix flow or an arbitrary flow regime. The process kinetics, in each case will be different and hence the design approach. The important UAF process kinetic parameters, influencing its design and operation, have been identified as the reaction rate constant (K), the order of reaction (n), maximum specific growth rate (μm), biomass yield coefficient (Y), saturation rate constant or half velocity constant (Ks) and maximum specific substrate utilization rate (k).

Although many researchers throughout the world have attempted to determine the flow regime of UAF, there seems to be significant disagreement among them as some consider it to follow the ideal plug flow regime (Wheatly and Cassel, 1985, \(^{69}\) and Young & Dahab, 1983, \(^{72}\)) whereas others feel that it nearly resembles the Complete Mix Reactor (CMR) (H. Young and J. Young, 1988, \(^{32}\) and Wheatly, 1982, \(^{67}\)) and hence have suggested the kinetics accordingly. However, it was felt that the UAF will neither follow plug flow nor the complete mix reactor flow regime, but will resemble that of an arbitrary reactor (Young & Young, 1991)\(^ {73}\), at least in terms of COD removal, as the flow moves up through the reactor. This will have effect on the process kinetics and hence on the design approach. The present study revolves around this hypothesis only. The present study was conducted with a primary aim of developing a simple mathematical model incorporating the process kinetic
parameters, to make the design of UAF rationally simple and accurate which removes the empiricism and hence makes it more acceptable to field engineers.

The thesis presents a critical review of the available literature on the various studies carried out on various aspects of UAF throughout the world. Young and McCarty (1969) did the pioneering work in developing UAF in 1969, since then several studies have been carried out by different researchers using different substrates under different operating conditions and variety of supporting media. However, the most significant modification of the original reactor developed by Young and McCarty (1968), has been the development and use of high porosity media. The use of high porosity media, in fact, has changed the character of the reactor, from basically a fixed film reactor to a fixed film reactor in which the contribution by the suspended bio-solids, entrapped in the numerous media pores, in the substrate removal is quite significant that is to say that the reactor no longer remains a biological reactor which can be modeled and designed on the basis of bio-film kinetics only.

Joo-Hova Tay, Kuan-Yeow Shao and S. Jeyseelan (1996) have concluded that the contribution by the suspended bio-solids, in the removal of COD, can be as high as 40%. Considering the fact that this will have effect not only on the overall behavior of the reactor, but also on the substrate removal rate and hence it cannot be ignored while developing the mathematical model to simplify the reactor design, which can become a simple design tool for field engineer. In the present study an attempt has been made to incorporate the contribution by suspended bio-solids in the overall substrate removal by UAF. In fact, up till now the researchers have modeled UAF on the bio-film kinetics only, ignoring the role of suspended bio-solids in the removal of substrate. This further complicates the development of a simple
mathematical model. As the development of mathematical model is expected to be primarily influenced by the reactor flow regime and process kinetics, the objectives of the present study have been,

(1) Determination of reactor flow regime i.e. the hydrodynamics characteristics of the reactor;

(2) Determination of process kinetic constants:

   (a) Reaction kinetic constants, viz. order of the reaction (n) and reaction rate constant (K);

   (b) Bio-kinetic constants, viz. maximum specific growth rate, (\(\mu_m\)), Half velocity constant (Ks) and maximum specific substrate utilization rate (k) by assuming the growth yield coefficient \(Y\);

(3) Developing mathematical models for different reactor flow regimes and validating the same by using the process kinetic constants as determined by operating the laboratory scale model.

The data generated for the above mentioned objectives have also been used to establish several relationships to provide deeper insight in the reactor performance, namely COD removal efficiency and OLR, COD removal profile along the height of the filter, substrate removal rate and OLR, dispersion number and OLR. Also Morrill Dispersion Index, Variance, Peclet Number and Dead space, which reflect the characteristics of the packed bed reactor, have been determined.

To determine the hydrodynamic characteristics of UAF, tracer studies were conducted, under different operating conditions by introducing 0.1 M NaCl as pulse tracer at the inlet and chloride was measured in the effluent at every 15 minutes. Using the tracer output data, so generated, the tracer response curves, in the form of Residence Time Distribution (RTD) curves, have been developed and presented at SPRERI: N S Varandani
figure no 4.3A to 4.3D. The RTD curves are skewed indicating deviation of UAF from the ideal plug flow as well as complete mix reactors. The tracer response has also been used to determine the extent of dispersion or mixing in the reactor under different hydraulic and organic loading rates through the determination of Dispersion number, Morrill dispersion index and Variance of distributions. The dispersion numbers at HLR 5.354 m³/m²d to 19.0 m³/m²d and OLR varying from 2 to 11 kg COD / m³ – d was observed to vary from 0.03 to 0.16 indicating the intermediate extent of mixing/dispersion which is characteristic of an arbitrary reactor. The Morrill dispersion index and variance which varied form 1.7 to 15.0 and 0.025 to 0.178 respectively re-confirm that the reactor behaves more like an arbitrary reactor rather than an ideal plug-flow reactor or CMR. As expected, the extent of mixing increased (as indicated by increasing dispersion number) with increasing OLR probably due to increase in gas generation.

Reactors I and II with different geometric configurations using the same support media i.e. nylon scrubbers were operated with primary aim to determine the hydrodynamic characteristics of UAF while reactor III was operated with emphasis on determination of process kinetics along with hydrodynamic characteristics as media used was different (sea shells) from that used in reactor I and II. The reactor performance data generated by operating reactor III through determination of COD, has been used to determine the process kinetic constants viz. the order of the reaction (n), the reaction rate constant (K), maximum specific growth rate (μm), the half – velocity constant (Ks), the maximum specific substrate utilization rate (k) respectively, under different operating conditions of hydraulic and organic loading rates. The significant determination has been that the reactor follows the fractional order of the reaction as it varied from 0.45 to 0.58 under different operating
Conditions, with an average value of 0.5. The reaction rate constant, for fractional
order reaction has been determined to remain fairly constant as $11 \text{ (mg/L)}^{0.5} \text{h}^{-1}$. The
values of $\mu_m$, $K_s$ and $k$, are determined to be 0.025 to 0.11 d$^{-1}$; 24 to 123 mg/L; 0.18 to
0.785 d$^{-1}$ respectively for OLR ranging from 2 to 11 kg/m$^3$-d and HLR ranging from
5.35 to 9.64 m$^3$/m$^2$-d by assuming the Growth Yield Co-efficient ($Y$) to be 0.14,
whereas the same bio-constants have been found to vary from 0.035 to 0.25 d$^{-1}$; 24 to
1310 mg/L; 0.25 and 1.786 d$^{-1}$ respectively along the height of the reactor and 0.01 to
0.18 d$^{-1}$; 46 to 1136 mg/L; 0.07 to 1.28 d$^{-1}$ respectively for different parts of the
reactor. For calculating the bio-kinetic constants, the basic assumption has been that
the bio-kinetics follows the Monod (1949)$^{44}$ relationships.

In order to provide a simple and rational approach to the design of UAF,
which, till now, has been approximate only, being based either on organic loading
rates, or on other thumb rules, an attempt has been made to develop mathematical
models for different reactor flow regimes / conditions such as an ideal plug flow,
complete mix flow (model II A and II B neglecting and considering endogenous
respiration of bacterial species respectively), non-ideal plug flow consisting number
of complete mix reactors in series (model III A & III B based on bio-kinetics and
reaction kinetics respectively), which resembles an arbitrary reactor. The
mathematical models have been postulated based on certain assumptions. The
significant incorporation, wherever possible, has been the contribution of suspended
biomass in the substrate removal, which has not been considered by any researcher
uptill now. In fact, such an incorporation made the simplification and derivation of the
mathematical models rather more complicated.

The thesis presents an attempt to validate the developed mathematical
model(s) by using the laboratory scale reactor performance data and the calculated
values of reaction kinetic and bio-kinetic constants. To simplify the verification process, computer programmes have been prepared using the “EXCELL” software and C language. The results of the “EXCELL” computer program runs are tabulated at table no. 7.1 to 7.5. The verification of various mathematical models indicate that the model III B, i.e. Non ideal plug flow model assumed to consist of Complete Mix Reactors in series based on reaction kinetics, gives results with least deviation from the real situation. An interesting observation being that the model offers least deviation or nearly satisfies the real situation for a particular COD removal efficiency, for a particular OLR, eg. the least deviations are obtained at COD removal efficiency of 89% for OLR 2, 81.5% for OLR 4, 78.5% for OLR 6 . However, the use of the model for COD removal efficiencies between 80-85% seems to be reasonable. For COD removal efficiencies lower than this, the deviation is positive while for efficiencies higher than this deviation is found to be negative. It is believed that for a biological reactor, an efficiency range of 80–85% is quite realistic and acceptable. Hence, the use of mathematical model III B seems to be acceptable and therefore, is recommended to be used by the field engineer for design of UAF.

Having confirmed that the UAF follows the arbitrary reactor kinetics, an attempt has also been made to develop the design nomographs, based on Wehner and Wilhem (1958) equation as suggested by D Thirumurthi (1969) for design of facultative ponds, which according to him also behave like an Arbitrary reactor. The limitation, however, being that the reaction is assumed to follow the first order reaction kinetics, as the solution of the differential equation for fractional order of the reaction presently seems virtually impossible or at least very difficult. However, necessary correction to account for it by calculating the ‘K’ values using first order and fractional order kinetics to determine the correction factor should be applied. In
fact, the ‘K’ value for fractional order reaction may take different value for different
support media. It is therefore recommended to use first order reaction constant, the
use of which does not introduce serious error in the design, as suggested by D.
Thrimurthi (1969)\textsuperscript{20} for design of facultative ponds.