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NON-LINEAR REGRESSION ANALYSIS IN UPFLOW ANAEROBIC SLUDGE BLANKET REACTOR

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ABSTRACT

A dimensionless approach was used to model the granule size variation in upflow anaerobic sludge blanket (UASB) reactor under different operating condition like organic loading rate, operating time, gas production rate, volatile suspended solids, suspended solids, upflow velocity, polymer loading, sludge volume index and effluent COD concentrations. Present study examines mathematically the effect of introducing polymers to enhance the granule size development in a UASB reactor especially in treatment of low strength wastewater in UASB reactor. The experimental results of investigators on different operating conditions were collected and subjected to dimensionless and non-linear regression analysis to model the enhancement of granule size in UASB reactor. The results using the dimensionless approach and the non linear regression show that better prediction of granule size variations for the data set based on the statistical estimates, errors and a satisfactory coefficient of determination (R2-values). The dimensionless approach of the present study can be successfully used to predict the granule size variations in UASB reactor.

KEYWORDS: Dimensionless approach, Granule size, Non-linear regression, Organic loading rate.

INTRODUCTION

As compared to other anaerobic treatment technologies, such as anaerobic filter, anaerobic sequencing batch reactor, anaerobic expanded bed and fluidized bed reactors, the UASB system performance is highly dependent on granulation and the type of organic wastewaters treated. Anaerobic granular sludge is the core component of a UASB process. Granulation is the process in which suspended biomass agglutinates to form discrete well – defined granules. Microbial granulation is a complex process, involving different trophic bacterial groups and their physico-chemical and microbiological interactions. Granulation initiated by bacterial adsorption and adhesion to inert matters or inorganic participates provides a better settling characteristics and granule stability (Liu et al., 2002; Ghangrekar et al., 2005). UASB process performance can be judged by evaluating its performance within as well as beyond the granulation period and or start-up phase, as the system behaviour is under transient conditions within the granulation period (Show et al., 2004; Wang et al., 2004; Bhunia et al., 2008; Chong et al., 2012). For stable performance of UASB reactor, granulation, its size and density play an important role. Successful performance of UASB reactor can be achieved within a short period, if granules are developed quickly within the sludge bed under the proper environmental and operating conditions within the reactor. Granulation process is affected by various factors like organic loading rate, upflow velocity, settling velocity, sludge volume index, gas production rate, liquid flow rate, specific methenogenic activity, VSS/SS ratio, polymer loading, Percent COD removal and effluent COD concentration (Show et al., 2004; Wang et al., 2004). Granulation is also affected by several other factors such as pH and alkalinity (Singh et al., 1999; Kalogo et al., 2001), temperature (Singh and Viraraghavan 2003), microbial ecology, production of exo-cellular polymeric substances by anaerobic bacteria (Morgan et al.,1990; Jia et al., 1996) nutrients and trace metals, heavy metals etc. (Hickey et al., 1989; Singh et al., 1999). Granules may range from 0.1 to 5 mm in size or even higher than 5 mm and are differentiated from flocculated sludge by their high shear strength (Schmidt and ahring et al., 1996; Show et al., 2004). Approximately 2-3 % of the granules in the reactors were reported in the size range of 0.5-4.5 mm by Tiwari et al., (2005). Yu et al., (2000) have documented that about 14 %

granules were observed larger than 4.0 mm in size in UASB reactor. After increment in the organic loading rate, the granule sizes were reduced due to shearing of granules caused by high flow velocity and possible washout of lighter microorganisms (Show et al., 2004; Ghangrekar et al., 2005; Bhunia et al., 2008). Sludge volume index (SVI) indicates the settling charecteristics of granules and reduction in SVI values show the better settling characteristics and improved performance of reactor (Show et al., 2004; Wang et al., 2004; Lertsittichai et al., 2007).

The present paper is devoted to model the granule size variation in UASB reactor using dimensionless approach by considering the important factors influencing the granulation and granule size variation such as organic loading rate (OLR), upflow velocity (V_{up}), settling velocity (SV), sludge volume index (SVI), gas production rate (Q_g), liquid flow rate (Q), specific methenogenic activity (SMA), VSS/SS ratio, effluent COD concentration(S_e), polymer loading (P_o) etc. for which experimental results of few investigators are available in the literature. Further, the mathematical function developed in this work has been tested for their dependency with operation time and prediction of granule size in UASB reactor.

DIMENSIONLESS APPROACH TO MODEL GRANULE SIZE
In the present work, a dimensionless approach using Buckinghum π - theorem has been applied to model the granule size (D_g). As evident from the literature, granulation process is dependent on several factors enumerated in the proceeding section and hence the granule size is considered to be dependent on several independent variables such as organic loading rate (OLR), flow rate (Q), gas production rate (Q_g), volatile suspended solids (VSS), suspended solids (SS), specific methenogenic activity (SMA), sludge volume index(SVI), operation time (T), time for which a particular OLR is kept constant (T_o), effluent COD concentration (S_e), polymer dose (P_o), upflow liquid velocity (V_{up}), granules settling velocity (SV) and reactor diameter (D_r). Therefore,

$$D_g = f(\text{VSS, SS, SMA, SVI, OLR, Q, }Q_g\text{, T, }T_o\text{, }S_e\text{, }P_o\text{, }V_{up}\text{, SV and }D_r) \qquad (1)$$

Using Buckinghum π - theorem the various dimensionless groups formed are-

$$\left(\frac{D_g}{D_r}\right), \left(\frac{V_{up}}{SV}\right), \left(\frac{VSS}{SS}\right), \left(\frac{SMA}{SVI \times OLR}\right), \left(\frac{Q}{Q_g}\right), \left(1+\frac{T}{T_o}\right) and \left(1+\frac{P_o}{S_e}\right) \qquad (2)$$

A constant integer (1) is added in last two dimensionless term to account the initial value of function and the control reactor operated without polymer dosing.

Therefore, (D_g/D_r) can be written as:

$$\left(\frac{D_g}{D_r}\right) = \Phi\left[\left(\frac{V_{up}}{SV}\right), \left(\frac{VSS}{SS}\right), \left(\frac{SMA}{SVI \times OLR}\right), \left(\frac{Q}{Q_g}\right), \left(1+\frac{T}{T_o}\right), \left(1+\frac{P_o}{S_e}\right)\right] \qquad (3)$$

The function represented by Eq. (3) can be used to model the granule diameter in UASB reactor.
A multiplier function containing all the above dimensionless groups of Eq. (3) can be written and tested for its dependency with time and is expressed as:

$$\left(\frac{D_g}{D_r}\right) = \left[\left(\frac{V_{up}}{SV}\right) \cdot \left(\frac{VSS}{SS}\right) \cdot \left(\frac{SMA}{SVI \times OLR}\right) \cdot \left(\frac{Q}{Q_g}\right) \cdot \left(1+\frac{T}{T_o}\right) \cdot \left(1+\frac{P_o}{S_e}\right)\right] \qquad (4)$$

Let us express the R.H.S of Equation (4) as F_{mj}

$$F_{mj} = \left[\left(\frac{V_{up}}{SV}\right) \cdot \left(\frac{VSS}{SS}\right) \cdot \left(\frac{SMA}{SVI \times OLR}\right) \cdot \left(\frac{Q}{Q_g}\right) \cdot \left(1+\frac{T}{T_o}\right) \cdot \left(1+\frac{P_o}{S_e}\right)\right] \qquad (5)$$

Where, F_{mj} is simple multipliers function and suffix m represents the simple multiplier function while 'j' represents the reactor number. Eq. (5) can be used to test its dependency on operation time (T). Further, the dependency of power function expressed by Eq. (6) below can also be tested with operation time 'T' and is expressed as.

$$F_{pj} = \left[\left(\frac{V_{up}}{SV} \right) \cdot \left(\frac{VSS}{SS} \right) \cdot \left(\frac{SMA}{SVI \times OLR} \right) \cdot \left(\frac{Q}{Q_g} \right) \cdot \left(1 + \frac{T}{T_o} \right) \cdot \left(1 + \frac{P_o}{S_e} \right) \right]^n \tag{6}$$

Where, F_{pj} is a power multiplier function for modelling the granule diameter, suffix p represents the power multiplier function, 'j' represents the reactor number and n is exponent of the power multiplier function. Another attempt was made to develop a non-linear multiplier function by raising the powers of each dimensionless groups of Eq. (3) and is expressed as:

$$\psi_{Pj} = \left[\left(\frac{V_{up}}{SV} \right)^a \cdot \left(\frac{VSS}{SS} \right)^b \cdot \left(\frac{SMA}{SVI \times OLR} \right)^c \cdot \left(\frac{Q}{Q_g} \right)^d \cdot \left(1 + \frac{T}{T_o} \right)^e \cdot \left(1 + \frac{P_o}{S_e} \right)^f \right] \tag{7}$$ Where,

ψ_{Pj} is a non linear power multiplier function containing each dimensionless term as power function used, suffix p represents the power function, 'j' as reactor number and a, b, c, d, e and f are indices raised to the dimensionless groups formed in Eq. (4). Eq. (6) can also be written as:

$$\left(\frac{D_g}{D_r} \right) = \left[\left(\frac{V_{up}}{SV} \right)^a \cdot \left(\frac{VSS}{SS} \right)^b \cdot \left(\frac{SMA}{SVI \times OLR} \right)^c \cdot \left(\frac{Q}{Q_g} \right)^d \cdot \left(1 + \frac{T}{T_o} \right)^e \cdot \left(1 + \frac{P_o}{S_e} \right)^f \right] \tag{8}$$

The indices a, b, c, d, e and f were determined by non-linear regression analysis by fitting the Eq. (7) using

NLINFIT tool in MATLAB 2010a. Equations (6), (7) and (8) have been tested on experimental data of Show et al.,

(2004) and the results are discussed in the succeeding sections.

Data collection
Show et al., (2004) studied the effect of cationic polymer ('AA 184 H') on reactor start up and granule development in six Reactors. Control reactor (R1) was operated without addition of polymer, while the other five reactors designated as R2, R3, R4, R5 and R6 were operated with different polymer concentrations of 0.02, 0.04, 0.08, 0.160 and 0.320 g/L respectively. The OLR was step increased stepwise by shortening the hydraulic retention time (HRT) and maintaining the influent COD concentration at 5000 mg/L throughout the study in all reactors. In order to develop functions describing simulations of granule size by using the experimental conditions and results of Show et al. (2004). Experimental data were read either from the figures or directly from the tables given by Show et al. (2004). Wherever, required the experimental data were suitably converted into desired units. In the present paper all experimental data of R1 and R4 reactors are used, either read form figure or table.

Methodology
Experimental results of Show et al. (2004) were used for linear or non-linear fitting of Eqs. (6), (7) and (8). A simple multiplier function as per Eq. (6) was fitted with linear fitting of (F_{mj}) with time to observe its dependency on time for reactors R1 and R4 using Microsoft excel software (results are not shown here). The dependency of non-linear

power multiplier function (ψ_{Pj}) was also tested as per Eq. (8) using Microsoft excel software for data pertaining to

the reactors R1 and R4. Thereafter, a non-linear regression analysis of Eq. (8) was performed for the simulation of

(D_g/D_r) for reactors (R1 and R4) and the non-linear power multiplier function (ψ_{Pj}) was developed using

NLINFIT tool of MATLAB 2010a. All the statistical analysis was carried out by using Microsoft excel software.

RESULTS AND DISCUSSION
Behaviour of Dg/Dr with developed different dimensionless groups
From equation 3, D_g/D_r is dependent on six different dimensionless groups. Using experimental results of show et al., (2004) for reactor R4, dependency of six dimensionless groups with D_g/D_r shown below in figure 1. Dependency

of D_g/D_r with these six dimensionless groups are in-built linear, power, exponential and logarithm in Microsoft excel software with relatively poor R^2 values and hence results are not shown here.
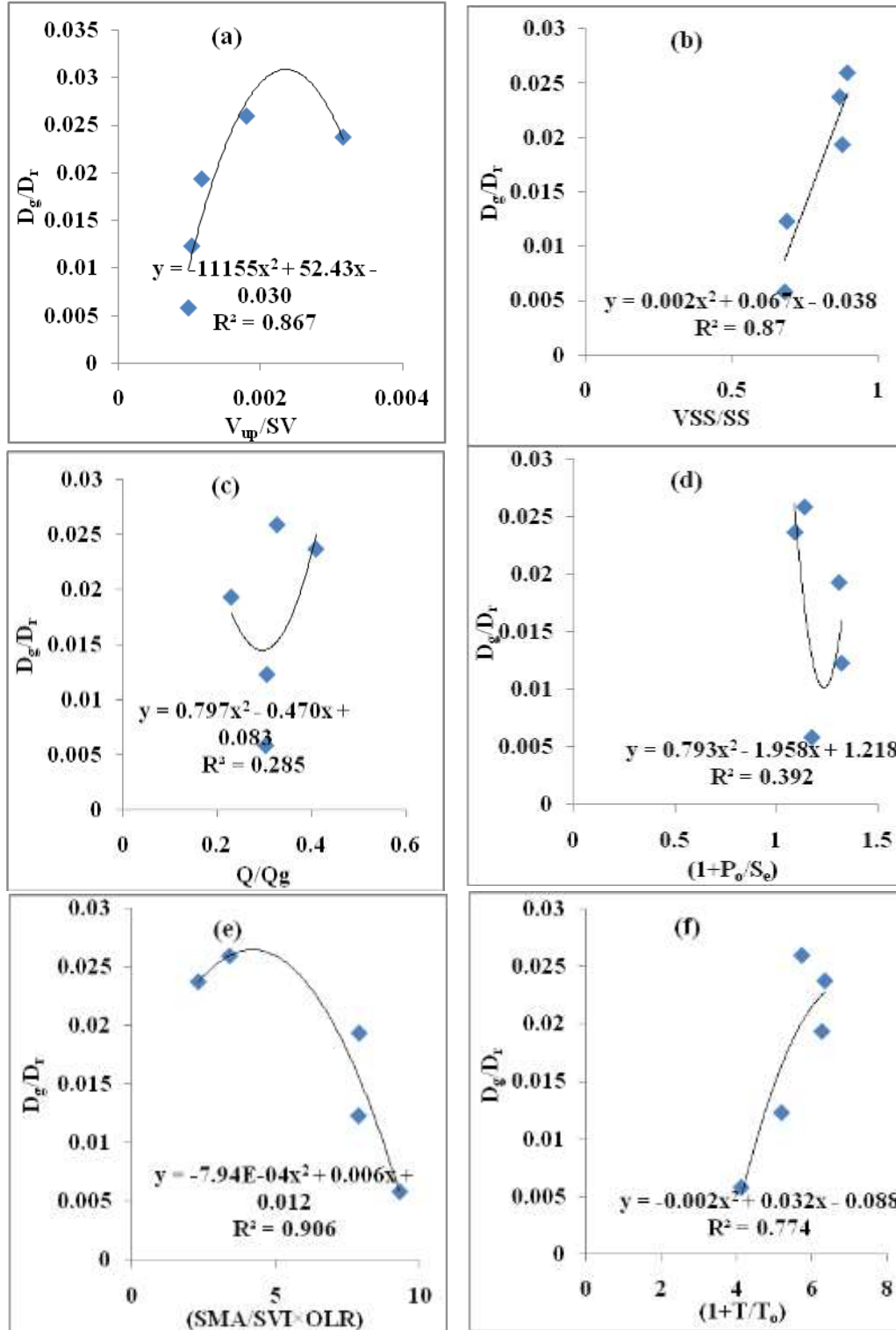

Figure 1: Dependency of six different dimensionless groups with D_g/D_r for reactor R4

In these fitting polynomial fitting give better relationship between the dimensionless groups and D_g/D_r. Dependency of dimensionless groups with D_g/D_r is polynomial in nature. The polynomial plots for reactor R4 are shown in figures 1 (a) to (f) along with their equations and R^2 values. From these polynomial fitting of experimental data, it is evident that dimensionless groups with D_g/D_r show some behaviour/relationship but R^2 values are observed quite low in these plots. The behaviour of four dimensionless groups (V_{up}/SV, SMA/SVI*OLR, $1+T/T_o$ and VSS/SS) shows better relationship with D_g/D_r and R^2 values are greater than 0.774. But, two dimensionless groups (Q/Q_g, $1+P_o/S_e$) relationship are not better with low R^2 values. Therefore, further investigations were needed to establish a better relationship between them.

Behaviour of D_g/D_r with Simple multiplier function (F_{mj})
Using the equation 6 simple multiplier function (F_{mj}) formed, dependency of this simple multiplier function, F_{mj} with D_g/D_r. Dependency of D_g/D_r with simple multiplier function are in-built linear, power, exponential and logarithm in Microsoft excel software with relatively poor R^2 values and hence are not shown here. In these fitting polynomial fitting give better relationship between the dimensionless group and D_g/D_r. Dependency of dimensionless groups with D_g/D_r is polynomial in nature. Using the experimental results of Show et al. (2004), for reactor R1 and R4 dependency of simple multiplier function with D_g/D_r are shown below in figure 2.
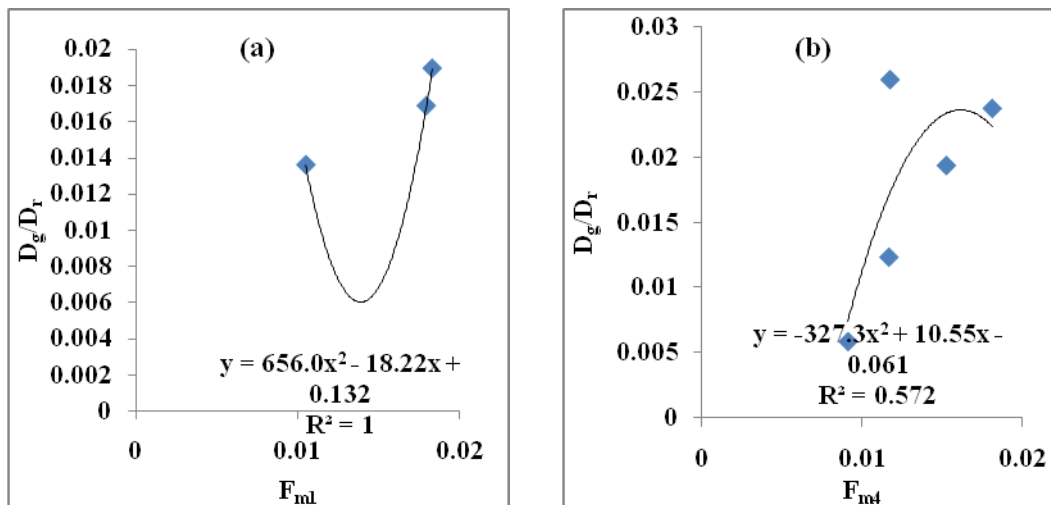

Figure 2: Dependency of simple multiplier function with D_g/D_r for reactor R1 and R4

Development of non linear power multiplier function (ψ_{pj}) containing each dimensionless term as power function

From the previous sections, it has been observed that simple multiplier function (F_{mj}) and power multiplier function (F_{pj}) do not correspond well with operating time while practically, it has been documented by various investigators that granule size in UASB reactor is a function of time. The function F_{mj}, F_{pj} is therefore, ruled out to simulate the

variation in granule size in UASB reactor. Further, a non-linear multiplier function (ψ_{pj}) containing powers of each dimensionless terms of Eq. (8) is developed by simulating the granule size term (L.H.S term of Eq. (8)) with the experimental results of Show et al. (2004) using NLINFIT tool of MATLAB 2010a and the resulting non-linear best fit equations for reactors R1 and R4 are summarized below in Eqs. (9) and (10).

$$\left[\frac{D_g}{D_r}\right]_{R1} = \left[\frac{V_{up}}{SV}\right]^{1.378} \left[\frac{VSS}{SS}\right]^{1.487} \left[\frac{SMA}{SVI \times OLR}\right]^{1.196} \left[\frac{Q}{Q_g}\right]^{-2.045} \left[1+\frac{T}{T_o}\right]^{0.483}$$

(9)

$$\left[\frac{D_g}{D_r}\right]_{R4} = \left[\frac{V_{up}}{SV}\right]^{0.089} \left[\frac{VSS}{SS}\right]^{2.184} \left[\frac{SMA}{SVI \times OLR}\right]^{-1.692} \left[\frac{Q}{Q_g}\right]^{-1.288} \left[1 + \frac{T}{T_o}\right]^{-1.788} \left[1 + \frac{P_o}{S_e}\right]^{-7.118} \quad (10)$$

Eqs. (9) and (10) are developed to describe the experimental granule size as represented by Show et al. (2004). From there equations, it is seen that the power of each dimentionless terms i.e. a, b, c, d, e and f of Eq.(8) varies from reactor to reactor. This is mainly due to different operating and loading conditions maintained in different reactors. Also, the variation in indices of each dimentionless term is non-consistant. Due to this reason the R.H.S functions in Eqs. (9) and (10) are different, but are capable to simulate well the experimental values, denoting R.H.S of Eqs (9) and (10) as ψ_{p1} to ψ_{p4} respectively. Based on above discussions, it has been observed that granules size is well simulated by model Eqs. (9) and (10). In order to observe the dependency of R.H.S terms of these equations, denoted by ψ_{pj} on operation time, the functions ψ_{pj} were plotted with D_g/D_r for reactors (R1 and R4) as shown in figure 3 (a) to (b).
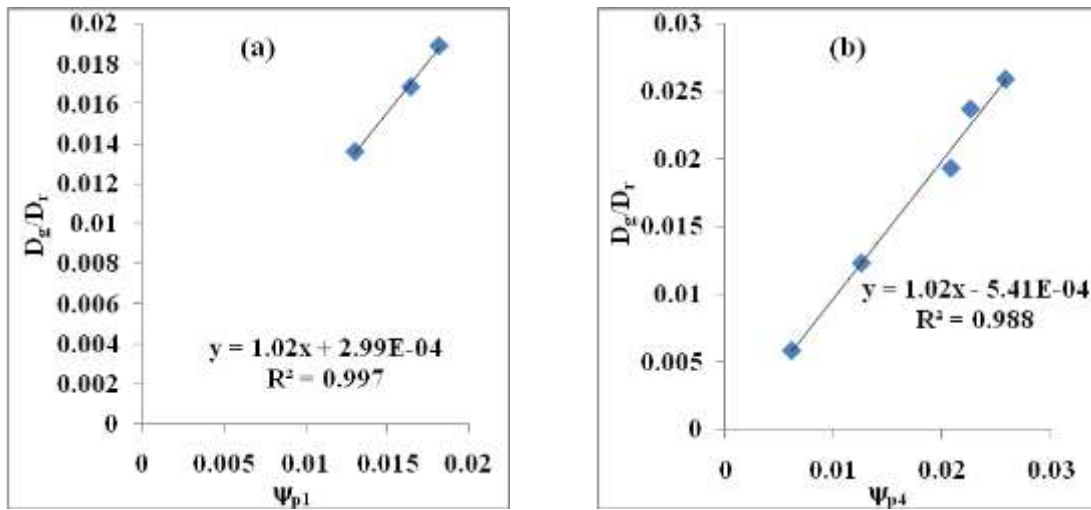

Figure 3: Variation of Dg/Dr with non linear power multiplier function for reactors (a) R1 and (b) R4

From these figures, it is seen that linear dependency exist between the function ψ_{pj} and D_g/D_r as evident from high R^2–values of linear fits in these cases. Percentage error between experimental and predicted D_g/D_r is shown below in Table 1.

Table 1: Percent error (%) between experimental and predicted (D_g/D_r) using function ψ_{pj}

	D_g/D_r(Exp.)	D_g/D_r(Pred.)	Error (%)		D_g/D_r(Exp.)	D_g/D_r(Pred.)	Error (%)
Reactor R1	0.01363	0.013008	4.566	**Reactor R4**	0.00583	0.006087	4.4
	0.01687	0.016417	2.688		0.01231	0.012522	1.725
	0.01893	0.018145	4.146		0.01935	0.020788	7.432
					0.02594	0.025817	0.474
					0.02373	0.022593	4.792

The percentage error in simulation of granule size using above best fit equations lies between 0.47% to a maximum of 7.43%, which is reasonable and within acceptable limit in such simulations. From the Table 1 it can be easily seen that the percent error is less than 7.5% in case of reactors R1 and R4 which shows that Eqs. (9) and (10) are suitable for simulation of granule size under the operating variables adopted in these reactors. Prediction of various statistical error estimates (SR, SEE, SSE, S.D and RMSE) between experimental and predicted Dg/Dr are given below in

Table 2. From Table 2, it is evident that small values of SR and SEE between experimental and simulated (D_g/D_r) are of the order of 10^{-5}, which shows a better correspondence in reactors R1 and R4. Small value of SSE is order of 10^{-8} indicates that less error between experimental and predicted values of (D_g/D_r) for reactors R1 and R4. Standard deviation of the order of 10^{-3} indicates that deviation from mean values is not much significant and the simulations are close to the experimental (D_g/D_r) values. Low value of RMSE indicates that very less difference between predicted D_g/D_r and observed experimental values.

Table 2: Statistical error estimates in experimental and predicted (D_g/D_r) using function $\square_{pj}$

Reactor	SR	SSE	SEE	S.D	RMSE
R1	3.0E-05	2.97E-08	4.97E-05	2.6E-03	1.50E-04
R4	1.0E-05	8.11E-08	9.0E-05	8.3E-03	1.62E-04

CONCLUSION

The present paper was aimed to model the granule size variation in UASB reactor using dimensionless approach to describe the granule size variation in UASB reactor. Dimensionless groups are first developed using 14 variables influencing granulation phenomenon and development of granule sizes in UASB reactor as gleaned from the literature. Non-linear power multiplier function containing powers of dimensionless terms were developed and nonlinear regression analysis was carried out using NLINFIT tool in matlab2010a. The nonlinear regression were performed using experimental results show et al. (2004), for laboratory scale UASB reactors in which polymer dose were varied to observe the granules development in UASB reactor. Behaviour of simple, power multiplier function (F_{mj}), (F_{pj}) and non-linear power multiplier function (ψ_{pj}) with operation time was studied and presented. The linear behaviour of F_{mj} with operation time was observed poor due to low R^2 values. On the other hand, the behaviour of (ψ_{pj}) with dimensionless granule size (D_g/D_r) were found better and non-linear regression equation (9) to (10) were developed with high R^2 value > 0.98 and good error estimates. The function (ψ_{pj}) was observed excellent in prediction of granule size variations in different UASB reactors and margin of error in prediction was maximum ±7.5% which was well within acceptable limit in such simulations. The behaviour of non-linear power multiplier function (ψ_{pj}) was tested for its dependency on operation time the granules size represented by non-linear power multiplier function (ψ_{pj}) were simulated well with experimental results of show et al. (2004). The linear behaviour of (ψ_{pj}) with operation time was found excellent with higher R^2 values and good error estimates. It was inferred that the function ψ_{pj} being dependent on operation time can be used to describe the kinetics of granule size variation UASB reactor.

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