Design of Isothermal Plug Flow Reactor Adsorption Tower for Sulphur Trioxide Hydration using Vanadium Catalyst

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***Abstract*— An isothermal plug flow reactor for the production of sulphuric acid over a range of degree of conversion ,X_A = 0.95 to 0.99 and reactor diameter, Di = 0.05 to 0.1m have been designed. The reactor which operates at atmospheric pressure is capable of producing 10,000 metric tons per annum. This reactor is designed with hastelloy because it possesses an excellent corrosion and sulphuric acid resistance properties. The reactor performance models are simulated with the aid of a Computer using MATLAB (R2007b).The results provided information for the functional parameters for the reactor which include; the reactor volume, space time, space velocity, rate of heat generation per unit volume of reactor, pressure drop, and length of reactor. The relationship between these parameters and the degree of conversion are presented graphically.**

***Index Terms*—About four key words or phrases in alphabetical order, separated by commas.**

I. INTRODUCTION

The advancements in the chemical engineering profession has brought to the fore the discovery of various chemicals compounds, which in a very large way affects or touches everyone in one way or the other every day. One of such chemical compounds that have found notable application is sulphuric acid. Sulphuric acid also known as oil of Vitriol is a dense, colourless, oily, corrosive liquid having a density of 1.84g/cm^3, a molecular formular of H_2SO_4 and a molar mass of 98.08g/mol. It is miscible with water in all proportions giving an exothermic reaction. This acid is a very important chemical commodity and was probably known before 16th century [1]. It was prepared by Johann Van Helmont [2], by destructive distillation of green vitriol (ferrous sulphate) and by burning sulphur. Sulphuric acid was also produced by Nordhausen from green vitriol but was expensive. A process for its synthesis by burning sulphur with potassium nitrate was first used by Johann Glauber in the 17th century and developed commercially by Joshua Ward in England in 1746 [3]. It was superseded by the lead chamber process which was invented by John Roebuck in 1746. [3]. Sulphuric acid was manufactured by the lead chamber process until the mid-1930s, but this process has been replaced by the contact process involving the catalytic oxidation of sulphur dioxide using vanadium pent oxide (V_2O_5) as catalyst.

The chemistry for the production of sulphuric acid is presented thus as follows:

$$S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)} \quad \text{-------------------------------} (1)$$

$$SO_{2(g)} + \tfrac{1}{2}O_{2(g)} \longrightarrow SO_{3(g)} \quad \text{-----------------------}(2)$$

$$SO_{3(g)} + H_2O_{(l)} \rightarrow H_2SO_{4(l)} \quad \text{---------------------------}(3)$$

The traditional methods of its production in pure form could not cope with the demand [3]. The lead chamber process and the contact process have been used to produce the acid in commercial quantity. The lead chamber process produces acid of very low grade, both in purity and concentration. However, the contact process produces acid of high concentration and purity but the process of its manufacture is very expensive. This process utilizes very expensive catalyst –Vanadium pent oxide. As a result the acid from this process is equally expensive.

Hence, to ensure availability and affordability of the product with acceptable quality, there is need to look for alternative methods of its production.

Substantial works have been done and documented on the kinetics of sulphuric acid production [4]. Literatures have shown that direct dissolution of sulphur trioxide in water to produce the acid is not done due to very high heat of reaction occasioned in the process. Instead sulphur trioxide is absorbed in concentrated sulphuric acid to form oleum, and subsequently diluted with water to form sulphuric acid of 98%-100% concentration.

Although the production of sulphuric acid is eminent and known globally. Related literatures have shown that numerous treaties have been written and published on it [Green wood et al, 1984] . The purpose of this research is to investigate into past works on the development of performance models for reactor types for the production of sulphuric acid, and to specifically identify and develop appropriate performance models for the areas that are deficient in past work.

However, little or no known published work had been recorded for the development of performance models for the production of the acid using semi-batch reactor, continuous stirred tank reactor, and plug flow reactor. This present work is aimed at addressing this seemingly neglected area.

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II. KINETICS ANALYSIS

The reaction mechanism as presented in equation (3) showed chain reaction characteristics [1]. Gibney and ferracid reported on the photo-catalysed oxidation of SO_3^{2-} by (dimethyl-glyoximato) $(SO_3)_2^{3-}$ and its (Co(dimethyl-glyoximato) $(SO_3)^3{}_2$. [5]

The work showed that the reaction

$$SO_3 + H_2O \longrightarrow H_2SO_4$$

is described as irreversible bimolecular chain reaction. Further research into the works of Erikson [6] and Huie, et al [7] established the reaction as second order reaction with rate constant K_2 = 0.3 mole/sec. Morokuma and Mugurama, performed abinitio calculation and determined the energetic barrier and established conclusively that the irreversible bimolecular nature of the reaction have $\Delta H_r = -25$kcal/mol at 25^0C. [8]

Following the outcome of the work of Chenier as cited above, the rate expression for the formation and production of sulphuric acid is summarized as in equation (3). [9]

$$-R_A = K_2 \; [SO_3] \; [H_2O] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Hence from equation (4) the amount of SO_3 and H_2O that have reacted at any time t can be presented as;

$$-R_A = K_2 \; [C_{A0} - C_{A0} \; X_A] \; [C_{Bo} - C_{A0} \, X_A] \cdots (5)$$

Where

C_{Ao} = Initial concentration of SO_3 (moles/Vol)
C_{Bo} = Initial concentration of H_2O (moles/Vol)
X_A = Fractional conversion of SO_3 (%)
$-R_A$ = Rate of disappearance of SO_3 (mole/ Vol/t)

In this work, the rate expression ($-R_A$) as in equation (4) will be used to develop the hypothetical plug flow reactor design equations with inculcation of the absorption coefficient factor as recommended in the works of Van-Krevelen and Hoftyzer (1948). This is achieved by modifying equation (5) as illustrated below. The hypothetical concentration profile of the absorption of sulphur trioxide by steam (H_2O) is represented in fig 1.

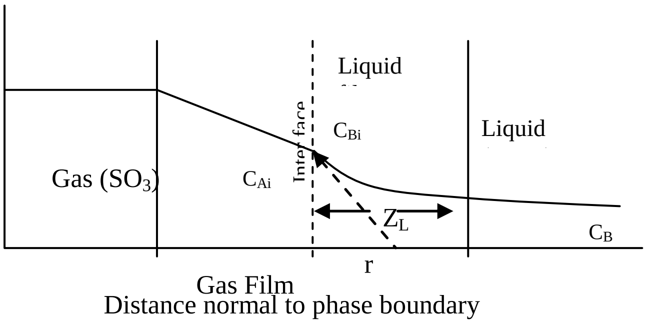

Figure 1 Absorption with Chemical Reaction

Sulphur trioxide (A) is absorbed into the steam (B) by diffusion. Therefore the effective rate of reaction by absorption is defined by

$$-R_A = \frac{rD_L}{Z_L} \left(C_{Ai} - C_{AL}\right) = rK_L \; (C_{Ai} - C_{AL}) \ldots\ldots (6)$$

Invoking the works of Krevelen and Hoftyzer, the factor r is related to C_{Ai}, D_L and K_L to the concentration of steam B in the bulk liquid C_{BL} and to the second order reaction rate constant K_2 for the absorption of SO_3 in steam solution. Thus

$$r = \left(K_2 D_L C_{BL}\right)^{1/2} \Big/ K_L \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Substituting equation (7) into (6) results in

$$-\, R_A = (C_A) \; C_{BL}^{1/2} \;\; K_2^{1/2} \;\; D_L^{1/2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Previous reports—Octave levenspiel 1999—showed that the amount of SO_3 (C_A) and steam (C_{BL}) that have reacted in a bimolecular type reaction with conversion X_A is C_{AO} X_A. Hence equation (8) can be rewritten as

$$-\, R_A = K_2^{1/2} \;\; D_L^{1/2} \left(C_{BO} - C_{AO} \; X_A\right)^{1/2} \; \left(C_{A0} - C_{A0} \, X_A\right)$$

$$= \;\; K_2^{1/2} \;\; D_L^{1/2} \, C_{A0}{}^{3/2} \;\; (m - X_A)^{1/2} \;\; (1 - X_A) \ldots. (9)$$

Where

$$m = \frac{C_{B0}}{C_{A0}} \quad \text{- The initial molar ratio of reactants}$$

$-R_A$ = Rate of disappearance of SO_3
K_2 = Absorption reaction rate constant
D_L = Liquid phase diffusivity of SO_3.
K_L = Overall liquid phase mass transfer coefficient
r = Ratio of effective film thickness for absorption with chemical reaction.

2.1 EVALUATION OF FRACTIONAL VOLUME CHANGE, ε_A

From equation (3), it is clear that change in volume takes place as the reaction proceeds. One mole of sulphur trioxide reacts with one mole of steam to form one mole of sulphuric acid. This change in volume can be expressed in terms of fractional change in volume of the reaction ($\boldsymbol{\varepsilon}_A$)

$$\boldsymbol{\varepsilon}_A = \frac{V_{XA=1} - V_{XA=0}}{V_{XA=0}} \quad \text{------------ (10)}$$

III. DEVELOPMENT OF PERFORMANCE MODELS

3.1 REACTOR VOLUME

In order to develop the necessary performance model equations for use in this work, we consider the reactor model as schematically presented in figures 2 and 3, noting that a isothermal case is being investigated thus necessitating the use of material balance equation.

The rate of reaction, R_A, as we know depends on both concentration and temperature.

This concentration dependence can be obtained by considering the material balance equation over the element of volume dV_R.

$$\left\{\begin{matrix}\text{Rate of inflow of}\\ \text{A into element}\\ \text{of volume}\end{matrix}\right\} = \left\{\begin{matrix}\text{Rate of outflow}\\ \text{of A from element}\\ \text{of volume}\end{matrix}\right\} + \left\{\begin{matrix}\text{Rate of disappearance}\\ \text{of A due to chemical}\\ \text{reaction with in}\\ \text{element of volume}\end{matrix}\right\} \quad (11)$$

For a plug flow reactor, we know, the rate of accumulation of A in element of volume is zero.

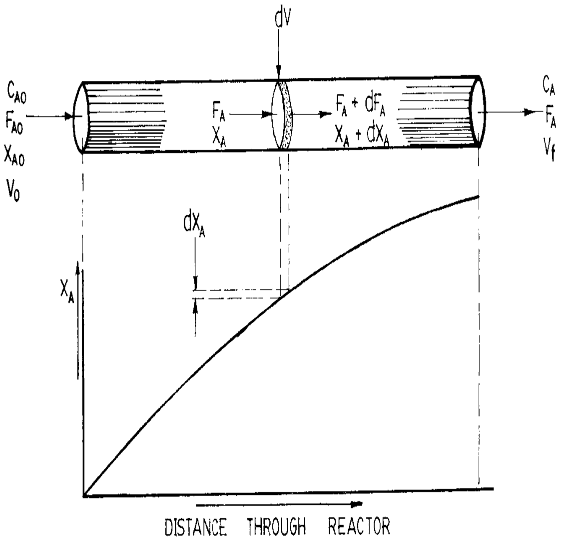

Figure 2 Hypothetical Tubular Reactor Unit and Performance

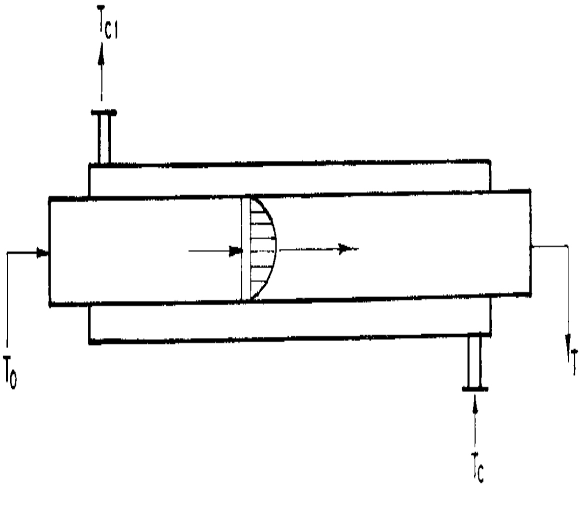

Figure 3 Hypothetical Heat Exchanger Unit

Rate of inflow of SO_3 into element of volume = F_A (12)

Rate of outflow of SO_3 from element of volume = $F_A + d\,F_A$ (13)

Rate of disappearance of SO_3 due to chemical reaction within element of volume = $(-R_R)\,d\,V_R$ (14)

substituting the above parameters into the material balance equation (11), gives

$$F_A = F_A + dF_A + (-R_A)dV_R \quad (15)$$

$$-dF_A = (-R_A)dV_R \quad (16)$$

Recall that

$$F_A = F_{A0}\,(1 - X_A)$$

Differentiating both sides give,

$$dF_A = -F_{A0}dX_A \quad (17)$$

Combining equations (16) and (17) gives

$$F_A\,dX_A = (-R_A)dV_R$$

$$dV_R = \frac{F_{A0}dX_A}{(-R_A)} \quad (18)$$

But,

$$-R_A = \frac{dC_A}{(dt)} = K^{1/2}_{2} D^{1/2}_{L} C^{3/2}_{A0}\,(m - X_A)^{1/2}\,(1 - X_A)$$

Substituting for R_A in equation (18) we have.

$$dV_R = \frac{F_{A0}dX_A}{K^{1/2}_{2}\,D^{1/2}_{L}\,C^{3/2}_{A0}\,(m - X_A)^{1/2}(1 - X_A)} \quad (19)$$

Integrating equation (19) we have

$$V_R = \frac{F_{A0}}{K^{1/2}_{2}\,D^{1/2}_{L}\,C^{3/2}_{A0}}\int_0^{XA}\frac{dX_A}{(m - X_A)^{1/2}(1 - X_A)} \quad (20)$$

$$V_R = \frac{F_{A0}}{K_2{}^{1/2}\,D_L\,{}^{1/2}\,C_{AO}{}^{3/2}}\left[\frac{2(m - X_A)^{1/2}}{1 - X_A}\right] \quad (21)$$

3.2 REACTOR LENGTH (L_R)

From the relationship

$$V_R = \frac{\pi D_i^2 L_R}{4}$$

$$L_R = \frac{4V_R}{\pi D_i^2} \quad (22)$$

Combining equations (21) and (22) we have

$$L_R = \frac{4F_{A0}}{\pi D_i^2 K_2{}^{1/2} D_L{}^{1/2} C_{AO}{}^{3/2}}\left[\frac{2(m - X_A)^{1/2}}{1 - X_A}\right] \quad (23)$$

3.3 SPACE TIME (T_s)

Space time is defined as the time required to process one reactor volume of feed measured at specified condition.

Mathematically,

$$T_s = \frac{V_R}{V_0}$$

$$T_s = \frac{1}{K_2^{1/2} D_L^{1/2} C_{A0}^{1/2}} \left(\frac{2(m - X_A)^{1/2}}{1 - X_A} \right) \quad (24)$$

3.4 SPACE VELOCITY(V_S)

Space velocity is defined as the number of reactor volume of feed which can be treated in unit time at specified condition.

Mathematically, $V_s = \frac{1}{T_s}$

$$V_s = \frac{K_2^{1/2} D_L^{1/2} C_{A0}^{1/2} (1 - X_A)}{2(m - X_A)^{1/2}} \quad (25)$$

3.5 PRESSURE DROP

3.1.6 PRESSURE DROP ALONG REACTOR LENGTH

The pressure drop (Δp) corresponding to the designed flow rate is often relatively small and does not usually impose any serious limitation on the condition of operation. The pressure drop must, of course be calculated as part of the performance parameter. Only for gases, at low pressure or, case of high viscosity e.g. polymers, is the pressure drop likely to have a major influence on the performance. [10]

Assuming Viscosity number, Nvis = I, we have

$$\Delta p = 8 J_h \left(\frac{L_2}{D_i} \right) \rho \frac{V^2}{2} \quad \text{(Sinnott, 2005)} \quad (3.19)$$

Where

J_h = Friction factor = $0.027/(N_{RE})^{0.2}$ (3.20)

L_R = Length of reactor (m)

D_i = Diameter of reactor (m)

ρ = Density of reaction mixture (kg/m^3)

V = Linear velocity of reaction mixture (m/s)

N_{RE} = GD_i/μ (3.21)

Where

G = Mass flow rate (kg/sm^2)

μ = Viscosity of mixture (kg/sm)

G = G_p/S_i (3.22)

Where

S_i = $\pi D_1^2/4$ (3.23)

G_p = Total product flow rate through the reactor (kg/sec)

Si = Cross-sectional flow area inside the reactor (m^2)

3.6 HEAT GENERATION PER REACTOR VOLUME (R_q)

The total heat generated is expressed as

$$Q = (-\Delta H_R) F_{A0} X_A \quad (30)$$

The heat generated per unit volume of reactor is given as

$$R_q = \frac{Q}{V_R} \quad (31)$$

$$R_q = \frac{(-\Delta H_R) X_A K_2^{1/2} D_L^{1/2} C_{AO}^{3/2} (1 - X_A)}{2(m - X_A)^{1/2}}$$

The computation of functional parameters of the reactor as shown in figs 2 and 3 is implemented in MATLAB and the computer flow chart describing the computation is illustrated in fig 4

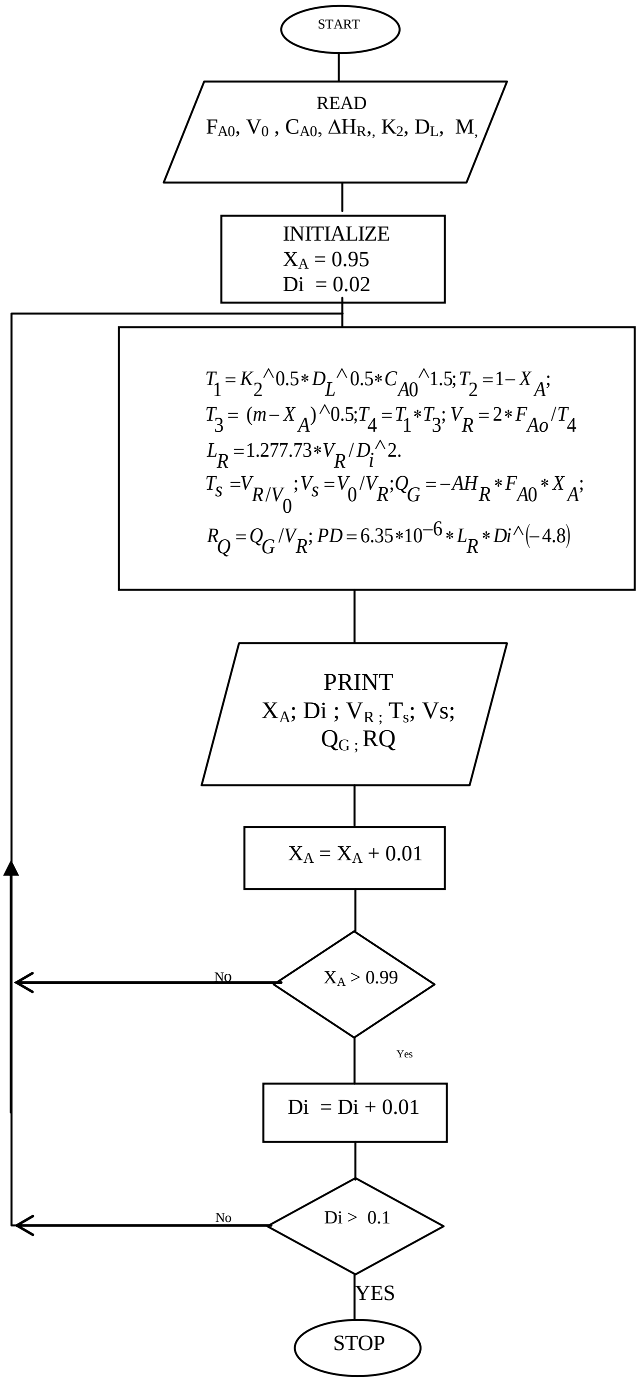

Figure 4 Flow chart describing the computation of isothermal PFR functional parameters.

3.7 THE REACTOR INPUT PARAMETERS

The reactor performance models developed in section 3.0 contain unknown parameters such as the molar flow rate, concentration and volumetric flow rate of reactant etc. these parameters have to be determined before equations 21 - 31 can be evaluated. The operating conditions and physical properties of the reactant are presented in table 1.

Table 1: Design data sheet.

Quantity	Symbol	Value	Unit
Initial concentration of SO_3	C_{A0}	16,759	mol/m^3
Absorption reaction rate constant	K_2	0.3	1/sec
Conversion degree	X_A	0.95-0.99	%
Reactant molar flow rate	F_{A0}	3.937	mol/sec
Diameter of tubular reactor	D_i	0.02to0.1	m
Molar ratio of reactants	m	1.0to 1.5	
Liquid phase diffusivity of SO_3	D_L	17	m^2/Sec
Volumetric flow rate of reactants	V_0	$2.352x10^{-4}$	m^3/Sec

IV. RESULTS AND DISCUSSION

Industrial reactors for the production of sulphuric acid over a range of degree of conversion $X_A = 0.95$ to 0.99 have been investigated and designed. The reactor have a capacity of $1.389x10^3$ Kg/hr of sulphuric acid. This reactor was designed with hastelloy because it has excellent corrosion and sulphuric acid resistance properties. The reactor performance models were simulated with the aid of MATLAB R2007b. The results provided information for the functional reactor parameters. These parameters include reactor volume, reactor length, space time, space velocity, and rate of heat generation per reactor volume. It is the purpose of this section to present and discuss the results of the reactor. The functional parameters of the reactor are tabulated in appendices A and B. The results showed that the reactor volume is dependent on degree of conversion X_A. The volume of the reactor would tend to infinity at 100% conversion. The variation of the reactor volume, space time, space velocity, heat generation per reactor volume, and reactor length as a result of sulphur trioxide addition to water with conversion degree is illustrated in figures 5, 6, 7, 8, and 9. From the results it was observed that the reactor volume, space time, and reactor length increases with increasing degree of conversion, while the space velocity, and heat generation per reactor volume decreases with increasing degree of conversion.

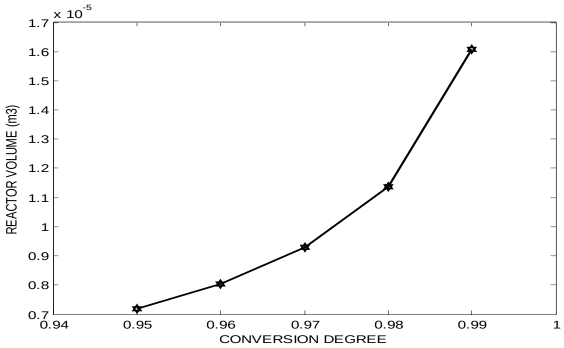

Figure 5 Plot of Reactor Volume against Conversion Degree for Isothermal PFR

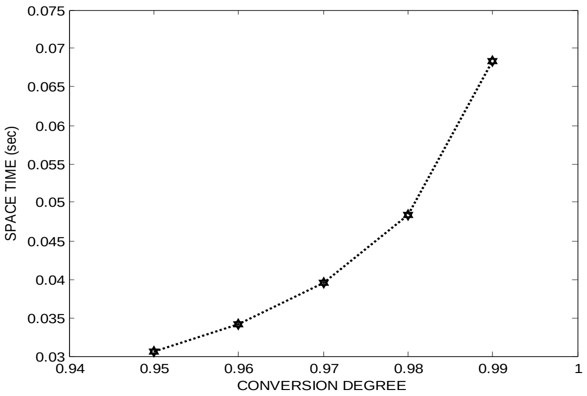

Figure 6 Plot of Space Time against Conversion Degree for Isothermal PFR

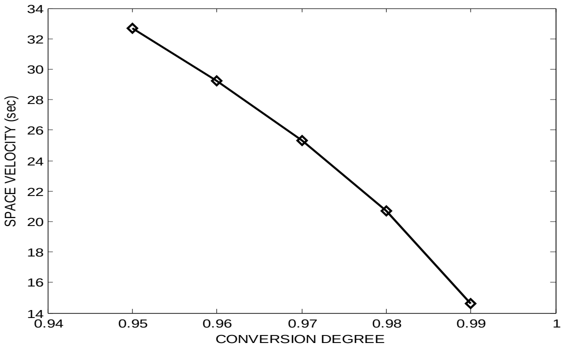

Figure 7 Plot of Space Velocity against Conversion Degree for Isothermal PFR

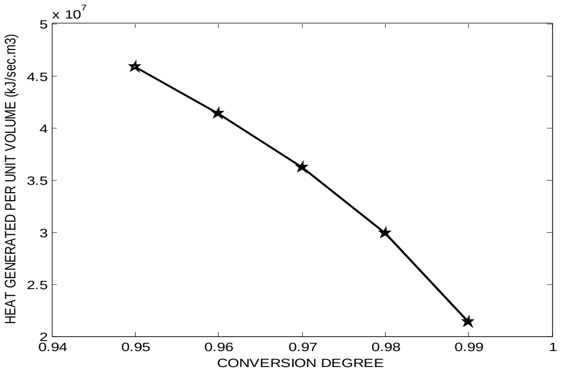

Figure 8 Plot of Heat Generated per unit Volume against Conversion Degree for Isothermal PFR

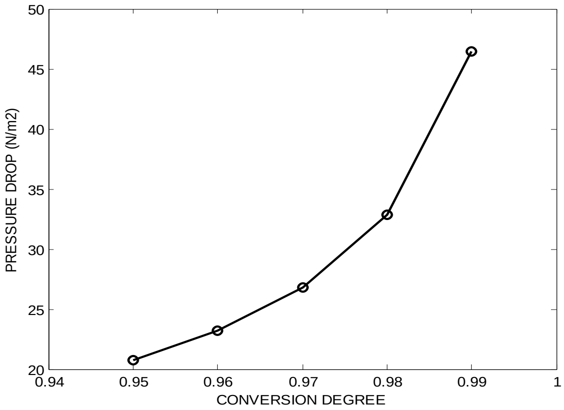

Figure 9 Plots of Pressure Drop against Conversion Degree for Isothermal PFR

From the results of the computation for the reactor it was found that, if the degree of conversion, X_A was 0.95, the reactor volume, V_R were 6.84E-05m^3 and 2.06E-05m^3 when the reactant molar ratio, m = 1.0 and 1.5 respectively but increase of X_A resulted in increase of the reactor volume up to 7.965E-04m^3 to 1.115E-04m^3 when X_A = 0.99 and m = 1.0 to 1.5.

V. CONCLUSION

An isothermal plug flow reactor has been designed for the production of ten thousand metric tons per year of sulphuric acid. Computer program was developed and utilized to simulate the reactor performance models over a conversion degree interval of X_A = 0.95 to 0.99. From the results of computation, it is clearly established that:

(a) When the diameter of the reactor, Di=0.02m, degree of conversion, X_A=0.95,the volume of the reactor, V_R are 7.20E-06m^3 and 2.39E-05m^3, the space time, T_S are 3.06E-02sec and 0.1015sec, the reactor length, L_R are 2.2909E-02m and 7.60E-02m, the rate of heat generation per reactor volume, RQ are 4.5795E07KJ/sec.m^3 and 4.5795E07KJ/sec.m^3 and the pressure drop, ΔP are 20.7851N/m^2 and 68.9365N/m^2 for the reactant molar ratio, m=1.0 and 1.5 respectively.

(b) When the degree of conversion, X_A=0.99 for the same lower reactor diameter, as specified above, the reactor volume, V_R are 1.609E-05m^3 and 1.149E-04m^3, the space time, T_S are 6.84E-02sec and 0.4885sec, the reactor length, L_R are 5.1195m and 0.3658m, the rate of heat generation per reactor volume, R_Q are 2.1342E07KJ/sec.m^3 and 2.1342E07KJ/sec.m^3 and the pressure drop, ΔP are 46.477N/m^2 and 331.9121N/m^2 for the reactant molar ratio, m=1.0 and 1.5 respectively.

(c) From (a) – (b) above, the reactor volume, space time, reactor length and the pressure drop were greater at the upper limits of conversion degree. While the rate of heat generation per unit reactor volume decreases as conversion degree increases.

(d)When the reactor diameter, Di=0.1m, degree of conversion, X_A=0.95, the reactor volume, V_R are 7.20E-06m^3 and 2.39E-05m^3, the space time, T_S are 3.06E-02esc and 0.1015sec, the reactor length, L_R are 9.1636E-04m and 3.0418E-03m, the rate of heat generation per reactor volume, R_Q are 4.5795E07KJ/sec.m^3 and 4,5795E07KJ/sec.m^3 and the pressure drop, ΔP are 3.671E-04N/m^2 and 1.2E-03N/m^2 for the reactant molar ratio, m=1.0 and 1.5 respectively.

(e) when the degree of conversion, X_A=0.99 for the same upper reactor diameter, as specified above, the reactor volume, V_R are 1.609E-05m^3 and 1.149E-04m^3, the space time, T_S are 6.84E-02sec and 0.4885sec, the reactor length, L_R are 2.0478E-03m and 1.4624E-02m, the rate of heat generation per reactor volume, R_Q are 2.1342E07KJ/sec.m^3 and 2.1342E07KJ/sec.m^3 and the pressure drop, ΔP are 8.208E-04N/m^2 and 5.90E-03N/m^2 for the reactant molar ratio, m=1.0 and 1.5 respectively.

(f) From (d) – (e) above, the reactor volume, space time, reactor length and the pressure drop were greater at the upper limits of conversion degree. While the rate of heat generation per unit reactor volume decreases as conversion degree increases.

Generally,

(g) At the lower limits of operating condition (i.e. conversion degree, X_A=0.95) increase in reactor diameter has no affect on reactor volume, space time and rate of heat generation per reactor volume. While the reactor length, and the pressure drop decrease as reactor diameter increases.

Similarly, at the upper limits of operating conditions (i.e. conversion degree, X_A=0.99), increase in reactor diameter has no affect on reactor volume, space time and rate of heat generation per reactor volume. While the reactor length and pressure drop decrease as reactor diameter increases.

VI. APPENDIX

APPENDIX 17A : ISOTHERMAL PFR(for m=1)

D_i (m)	X_A	V_R(m^3)*10^{-4}	L_R (m)*10^{-2}	T_S (sec)	V_S (sec^{-1})	R_q(kJ/sec.m^3)*10^7	ΔP (N/m^2)
.02	0.95	0.0720	2.2909	0.0306	32.6862	4.5795	20.7851
.02	0.96	0.0805	2.5614	0.0342	29.2354	4.1391	23.2385
.02	0.97	0.0929	2.9559	0.0395	25.3186	3.6219	26.8335
.02	0.98	0.1138	3.6209	0.0484	20.6726	2.9878	32.8642
.02	0.99	0.1609	5.1195	0.0684	14.6177	2.1342	46.4770

APPENDIX 17A: ISOTHERMAL PFR (for m=1)

D_i(m)	X_A	V_R (m^3)*10^{-4}	L_R(m)*10^{-3}	T_S (sec)	V_S(sec^{-1})	R_Q(kJ/sec.m^3)*10^7	ΔP (N/m^2)

.05	0.95	0.0720	3.6655	0.0306	32.6862	4.5795	0.0409
.05	0.96	0.0805	4.0982	0.0342	29.2354	4.1391	0.0457
.05	0.97	0.0929	4.7295	0.0395	25.3186	3.6219	0.0528
.05	0.98	0.1138	5.7935	0.0484	20.6726	2.9878	0.0647
.05	0.99	0.1609	8.1913	0.0684	14.6177	2.1342	0.0915

APPENDIX 17A: ISOTHERMAL PFR(for m=1)

D_i(m)	X_A	V_R(m^3) *10^{-4}	L_R(m)*10^{-4}	T_S (sec)	V_S(sec^{-1})	R_q(kJ/ sec.m^3)*10^7	ΔP(N/ m^2)*10^{-3}
.10	0.95	0.0720	9.1636	0.0306	32.6862	4.5795	0.3671
.10	0.96	0.0805	10.2455	0.0342	29.2354	4.1391	0.4104
.10	0.97	0.0929	11.8236	0.0395	25.3186	3.6219	0.4739
.10	0.98	0.1138	14.4836	0.0484	20.6726	2.9878	0.5804
.10	0.99	0.1609	20.4782	0.0684	14.6177	2.1342	0.8208

APPENDIX 17B: ISOTHERMAL PFR (for m=1.5)

D_i(m)	X_A	V_R (m^3)*10^{-3}	L_R(m)	T_S (sec)	V_S(sec^{-1})	R_Q(kJ/ sec.m^3) *10^7	ΔP (N/m^2)
02	0.95	0.0239	0.0760	0.1015	9.8553	4.5795	68.9365
.02	0.96	0.0296	0.0941	0.1257	7.9569	4.1391	85.3837
.02	0.97	0.0390	0.1243	0.1660	6.0237	3.6219	112.7859
.02	0.98	0.0580	0.1847	0.2467	4.0542	2.9878	167.5752
.02	0.99	0.1149	0.3658	0.4885	2.0469	2.1342	331.9121

APPENDIX 17B: ISOTHERMAL PFR (for m=1.5)

D_i(m)	X_A	V_R (m^3)*10^{-3}	L_R(m)	T_S (sec)	V_S (sec^{-1})	R_Q (kJ/sec.m^3) *10^7	ΔP (N/m^2)
.05	0.95	0.0239	0.0122	0.1015	9.8553	4.5795	0.1357
.05	0.96	0.0296	0.0151	0.1257	7.9569	4.1391	0.1680
.05	0.97	0.0390	0.0199	0.1660	6.0237	3.6219	0.2220
.05	0.98	0.0580	0.0295	0.2467	4.0542	2.9878	0.3298
.05	0.99	0.1149	0.0585	0.4885	2.0469	2.1342	0.6532

APPENDIX 17B: ISOTHERMAL PFR (for m=1.5)

D_i(m)	X_A	V_R (m3)*10-3	L_R(m) *10-3	T_S (sec)	V_S (sec-1)	R_Q (kJ/sec. m3) *107	ΔP (N/m2)
.10	0.95	0.0239	3.0418	0.1015	9.8553	4.5795	0.0012
.10	0.96	0.0296	3.7673	0.1257	7.9569	4.1391	0.0015
.10	0.97	0.0390	4.9636	0.1660	6.0237	3.6219	0.0020
.10	0.98	0.0580	7.3818	0.2467	4.0542	2.9878	0.0030
.10	0.99	0.1149	14.6236	0.4885	2.0469	2.1342	0.0059

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