IJESRT

INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

Isothermal Continuous Stirred Adsorption Tower (CSAT) for Vanadium Catalyst Based Sulphur Trioxide Hydration Process

M. F. N Abowei and T. O Goodhead
* Department of Chemical/Petrochemical Engineering Rivers State University of Science & Technology
Port Harcour,   Nigeria

Abstracts

Catalytic hydration of sulphur trioxide results to production of sulphuric acid and it is industrially very important chemical specie due to the associated uses. Hence the continuous search for the development of suitable design model to optimize its production capacity for reactor types is eminent. Therefore presented in this paper is development of design models for performance evaluation of continuous stirred adsorption tower (CSAT) for sulphur trioxide hydration process using vanadium catalyst at isothermal condition. The design models were stochastically appraised and found to be capable of simulating performance dimensions as a function of kinetic parameters. . These performance dimensions include tower volume, height, space time, space velocity, and rate of heat generation per unit volume. The developed performance models were generalized to accommodate any CSAT plant capacity design basis as a function of fractional conversion. The proposed performance dimensions design models could also be used to develop the heat exchanger functional parameters aimed at achieving the isothermal condition of the hydration process. The model equations were further simulated to evaluate the stipulated performance dimensions using Matlab R2007B within the operational limits of conversion degree at constant temperature. The results of the performance dimensions showed a dependable relationship with fractional conversion.

Keywords: Isothermal, CSAT, Design, Sulphur trioxide, hydration, Performance.

Introduction

The continue search for the most suitable reactor models to optimize sulphuric acid production is increasing globally (Austein ,1984, Duecker and West, 1975 and Faith, 1965). This is due to the numerous industrial and domestic applications of sulphuric acid. Sulphuric acid otherwise called oil of vitrol and king of chemicals is a diprotic acid with structural formula presented in figure 1.
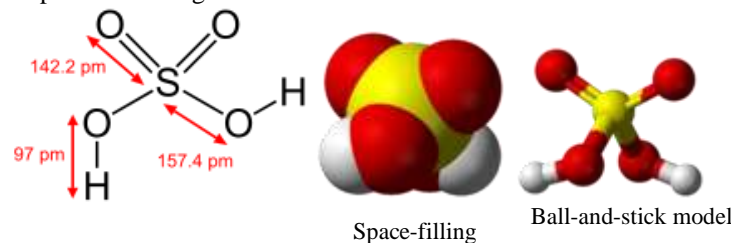

Space-filling   Ball-and-stick model

*Figure 1: Structural formula of Sulphuric acid*

Sulphuric acid possesses high ionization and dissociation capacities that influence its reactivity with other chemicals resulting to useful finished industrial products. Such sulphuric acid reactivity finished products includes;

- Sulfuric acid ionises in water in two stages: $H_2SO_4(l) + H_2O(l) \rightarrow HSO_4^-(aq) + H_3O^+(aq)$
  $$HSO_4^-(aq) + H_2O(l) \rightleftharpoons SO_4^{2-}(aq) + H_3O^+(aq)$$
- Sulfuric acid is a strong acid (complete dissociation in water, K_a approaches infinity)
- Sulfuric acid reactions:
  sulfuric acid + metal $\rightarrow$ metal sulfate + hydrogen gas
  sulfuric acid + carbonate $\rightarrow$ metal sulfate + carbon dioxide gas + water
  sulfuric acid + base $\rightarrow$ salt + water
 sulfuric acid + ammonia $\rightarrow$ ammonium sulfate

- Sulfuric acid can take part in redox reactions.

Other Uses of Sulfuric Acid (H_2SO_4) that attract global attention are**;**

- Sulfuric acid is the electrolyte used in lead-acid batteries (accumulators)
- Sulfuric acid is important in the production of fertilizers such as ammonium sulfate (sulfate of ammonia), $(NH_4)_2SO_4$, and superphosphate, $Ca(H_2PO_4)_2$, which is formed when rock phosphate is treated with sulfuric acid.
- Sulfuric acid is used to remove oxides from iron and steel before galvanising or electroplating
- Concentrated sulfuric acid (18M) is used as a dehydrating agent, that is, to remove water, since it has a tendency to form hydrates such as $H_2SO_4.H_2O$, $H_2SO_4.2H_2O$, etc.
  Sulfuric acid is often used to dry neutral and acidic gases such as N_2, O_2, CO_2 and SO_2
  Sulfuric acid will "suck" water out of carbohydrates and some other organic compounds which contain oxygen and hydrogen. For example, sulfuric acid will "suck" water out of sucrose, $C_{12}H_{22}O_{11}(s)$, (cane sugar) to produce a spongy mass of carbon:

$$C_{12}H_{22}O_{11}(s) + 11H_2SO_4 \rightarrow 12C(s) + 11H_2SO_4.H_2O$$
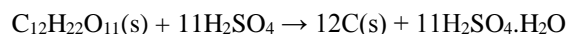
- Sulfuric acid is used in the production of nitroglycerine, an inorganic ester & organic nitrate, which is used as an explosive but can also be used as a *vasodilator*, a substance that dilates blood vessels and can be used in the treatment of certain types of heart disease:

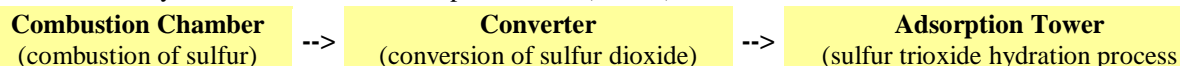$$CH_2ONO_2$$
$$|$$
$$CHONO_2$$
$$|$$
$$CH_2ONO_2$$
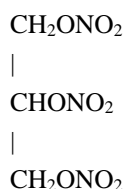
Although the production of sulphuric acid is eminent and known globally, related literatures have shown that numerous treaties have been written and published on it Corma et al(2005), York Fair (1968) The purpose of this research is to investigate into past works on the development of performance models 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.
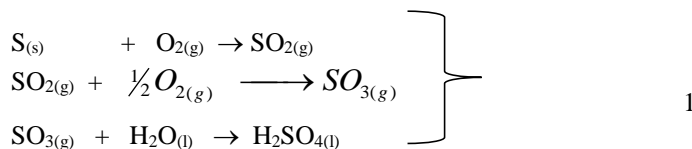
However, little or no known published work had been recorded for the development of performance models for the production of the acid using batch, continuous stirred tank reactor, and plug flow reactors. Recently works of Goodhed and Abowei (2014) focused on development of design models for H_2SO_4 production based on semi batch, isothermal plug flow (IPF) non-isothermal plug flow (NIPF) and non- isothermal continuous adsorption tower. Therefore, in this present paper we considered development of design equations for the simulation of isothermal continuous stirred adsorption tower (CSAT) primarily to evaluate the performance as a function of kinetic parameters which seemly not appraised.

2.0 KINETIC EVALUATION

The stoichiometry in the manufacture of Sulphuric Acid (H_2SO_4) is summarized as follows;

| **Combustion Chamber** (combustion of sulfur) | --> | **Converter** (conversion of sulfur dioxide) | --> | **Adsorption Tower** (sulfur trioxide hydration process |

The *Contact Process* is a process involving the catalytic oxidation of sulfur dioxide, SO_2, to sulphur trioxide, SO_3. A vanadium catalyst (vanadium (V) oxide) is also used in this reaction in order to speed up the rate of the reaction. The current work looked at the development of performance evaluation models for vanadium catalyst based isothermal continuous stirred adsorption tower sulphur trioxide hydration process in the production of sulphuric acid. The stoichiometric chemistry is given as,

$$S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$$
$$SO_{2(g)} + \tfrac{1}{2}O_{2(g)} \longrightarrow SO_{3(g)}$$
$$SO_{3(g)} + H_2O_{(l)} \rightarrow H_2SO_{4(l)}$$

1

Substantial works had been done and documented on the kinetics of sulphuric acid production (Chrstenson et al (1999). 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.

The reaction mechanism as presented in equation (3) showed chain reaction characteristics [Austin, 1984]. Gibney and ferracid (1994) reported on the photo-catalysed oxidation of SO_3^{2-} by (dimethyl-glyoximato) $(SO_3)_2^{3-}$ and its $(Co(dimethyl-glyoximato) (SO_3)^3_2$.

The work showed that the reaction

$$SO_3 \ + \ H_2O \longrightarrow H_2SO_4 \ \text{--- 2}$$
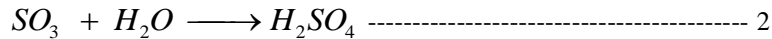
is described as irreversible bimolecular chain reaction. Further research into the works of Erikson, [1974] and Gibney, (1994) established the reaction as second order reaction with rate constant K_2 = 0.3 mole/sec. Blinding (1953) performed abinitio calculation and determined the energetic barrier and established conclusively that the irreversible bimolecular nature of the reaction have ΔH_r = -25kcal/mol at 25^0C.

Following the outcome of the work of Chenier (1987), Charles (1977) and Ancheya (1997) as cited above, the rate expression for the formation and production of sulphuric acid is summarized as in equation 2.

$$-R_A \ = \ K_2 \ [SO_3] \ [H_2O] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 3$$

Hence from equation 3 the amount of SO_3 and H_2O that have reacted at any time t can be presented as;

$$- R_A \ = \ K_2 \ [C_{A0} \ - \ C_{A0} \ X_A] \ [C_{Bo} \ - \ C_{A0} X_A] \ldots\ldots\ 4$$

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 develops the hypothetical continuous stirred tank reactor tower design equations with inculcation of the absorption coefficient factor as recommended in the works of Van-Krevelen and Hoftyger cited in Austein (1984) and Danner,(1983). This is achieved by modifying equation 4 as illustrated below. The hypothetical concentration profile of the absorption of sulphur trioxide by steam (H_2O) is represented in fig.2
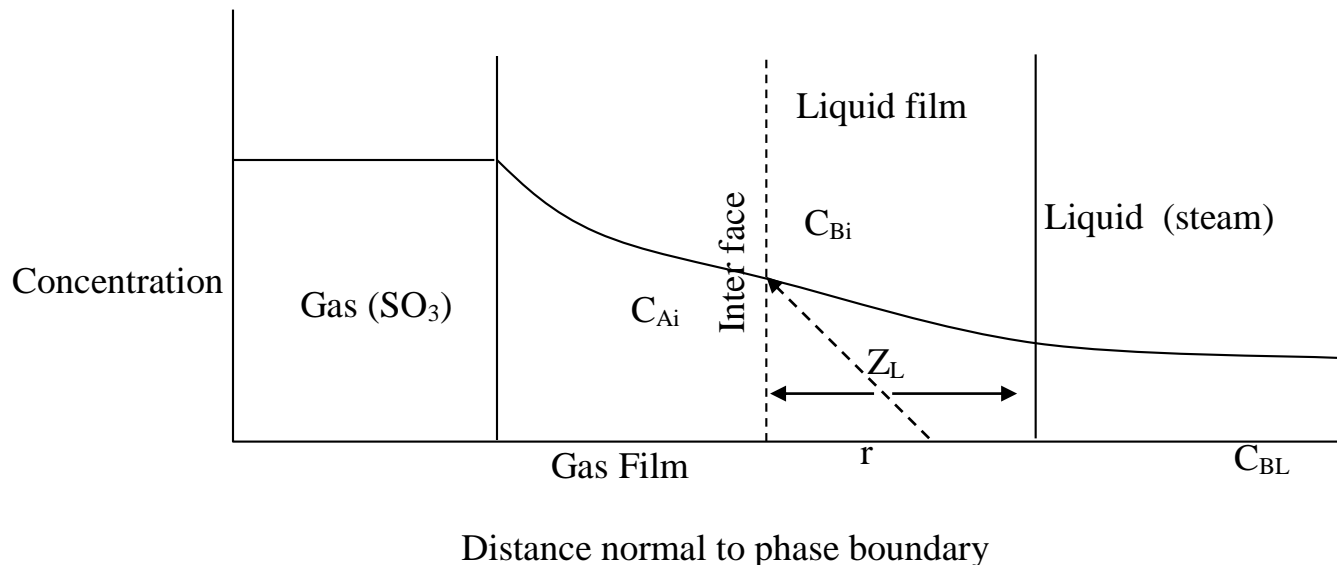

Figure 2: *Absorption with chemical Reaction*

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

$$- R_A \ = \ \frac{rD_L}{Z_L} \ (C_{Ai} \ - \ C_{AL}) \ = \ rK_L \ (C_{Ai} - C_{AL}) \ldots\ldots\ldots\ldots\ldots\ldots\ 5$$

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

$$r = \left(K_2 D_L C_{BL}\right)^{\frac{1}{2}} \Big/ K_L \quad \text{..................} 6$$

Substituting equation 6 into 5 results in

$$-R_A = (C_A)\, C_{BL}^{\frac{1}{2}}\, K_2^{\frac{1}{2}}\, D_L^{\frac{1}{2}} \quad \text{.....................................} 7$$

Previous reports (Octave levenspiel, 1999, Dewachtere et al, 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 7 can be rewritten as

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

$$= K_2^{\frac{1}{2}}\, D_L^{\frac{1}{2}}\, C_{A0}^{\frac{3}{2}}\, (m - X_A)^{\frac{1}{2}}\, (1 - X_A) \quad \text{.........................} 8$$

Where

$$m = \frac{C_{B0}}{C_{A0}}$$

m   =   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

Materials and method
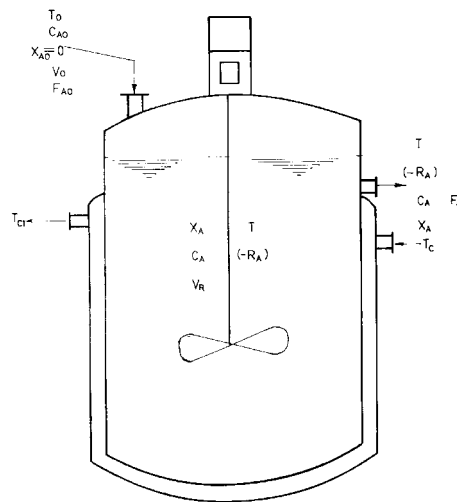**Development of performance model**

Fig. 3. Hypothetical model of a Jacketed CSAT

Reactor Volume
The performance equation for isothermal mixed flow reactor makes an accounting of a given component within an element of volume of the system. But since the composition is uniform throughout, the accounting may be made about the reactor as a whole. Octave Levenspel (1986) and Coulson & Richardson (1979, and 1979; Forgler, 1994 and Forment, 2001). Thus,

Input = Output + disappearance by reaction + accumulation ……………   9
Where
 Accumulation   = O for steady state process.
If $F_{AO} = V_0 C_{A0}$ is the molar feed rate of SO_3 to the reactor, then considering the reactor as a whole we have

Input of SO_3, moles/time = F_{A0} $(1 - X_A)$ = F_{A0} 10
Output of SO_3, moles/time = F_A = F_{A0} $(1 - X_A)$ 11
Disappearance of SO_3 by reaction, moles/time = $(-R_A)$ V_R 12
Introducing the three terms in the material balance
Equation 9 yields.
$F_{A0} X_A = (-R_A) V_R$ 13
Which on re-arranging becomes

$$V_R = \frac{F_{Ao} X_A}{(-R_A)} \qquad\qquad 14$$

But, $-R_A = \dfrac{dC_A}{dt} = K_2^{\frac{1}{2}}\, D_L^{\frac{1}{2}}\, C_{A0}^{\frac{3}{2}}\, (m - X_A)^{\frac{1}{2}}\, (1 - X_A)$

Substitution in equation 14 results in

$$V_R = \frac{F_{Ao} X_A}{K_2^{\frac{1}{2}}\, D_L^{\frac{1}{2}}\, C_{AO}^{\frac{3}{2}}\, (m - X_A)^{\frac{1}{2}}\, (1 - X_A)} \qquad\qquad 15$$

F_{A0} = Molar feed rate of SO_3, (mole/sec)
X_A = Conversion degree
C_{A0} =   Initial concentration of SO_3, (mole/m^3)
K_2 =   Absorption reaction rate constant, (1/sec)
D_L = Liquid phase diffusivity of SO_3, (m^2 /sec)
M   = Initial molar ratio of reactants.

Space Time
 The space time T_s in mathematically defined as,

$$T_s = \frac{Volume \ of \ reactor}{Volumetric \ flowrate}$$

$$= \frac{V_R}{V_o} \qquad\qquad 16$$

Putting equation 15 into 16 results in

$$T_s = \frac{X_A}{K_2^{\frac{1}{2}}\, D_L^{\frac{1}{2}}\, C_{AO}^{\frac{1}{2}}\, (m - X_A)^{\frac{1}{2}}\, (1 - X_A)} \qquad\qquad 17$$

3.1.3 Space Velocity
This is the reciprocal of the space time Ts and expressed mathematically as

$$V_S = \frac{1}{T_s} = \frac{V_0}{V_R} \qquad\qquad 18$$

Then from equation 17 it is possible that

$$V_s = \frac{K_2^{1/2} \; D_L^{1/2} \; C_{Ao}^{1/2} \; (m - X_A)^{1/2} \; (1 - X_A)}{X_A} \qquad\qquad 19$$

Reactor Height
Considering a reactor with cylindrical shape we have

$$V_R = \pi r^2 h$$

$$h = \frac{V_R}{\pi r^2} \qquad\qquad 20$$

$$= \frac{F_{AO} \; X_A}{\pi r^2 \; K_2^{1/2} \; D_L^{1/2} \; C_{AO}^{3/2} \; (m - X_A)^{1/2} \; (1 - X_A)} \qquad\qquad 21$$

For $0.1m \leq r \leq \underline{1.0m}$

Heat Generation Per Reactor Volume
Heat flow rate of CSAT is a function of heat of reaction for SO_3 addition to water, molar feed rate and the conversion degree. It is mathematically expressed (Abowei,1989) as;

$$Q = (-\Delta H_R) \; F_{A0} \; X_A \qquad\qquad 22$$

The heat generation per reactor volume is obtained by dividing both sides of equation 22 by the reactor volume and substituting equation 15 accordingly gives,

$$R_q = \frac{Q}{V_R} = (-\Delta H_R) K_2^{1/2} D_L^{1/2} C_{A0}^{3/2} (m - X_A)^{1/2} (1 - X_A) \qquad\qquad 23$$

3.2 COMPUTATIONAL PROCEDURE
The developed models as presented in section 3 .1 were programmed using MATLAB and the flow chart describing the computational procedure is given in Fig 4. Performance dimensions such as CAST volume, length, space time, space velocity, heat generation per unit volume, and functional parameters capable of maintaining isothermal conditions were cleverly inculcated into the computer algorithm. The equations of these performance measures were expressed as a function of fractional conversions and other kinetic parameters at constant operational temperature. The computational algorithm exploited for the evaluation of performance parameters as a function of kinetic data is presented in figure
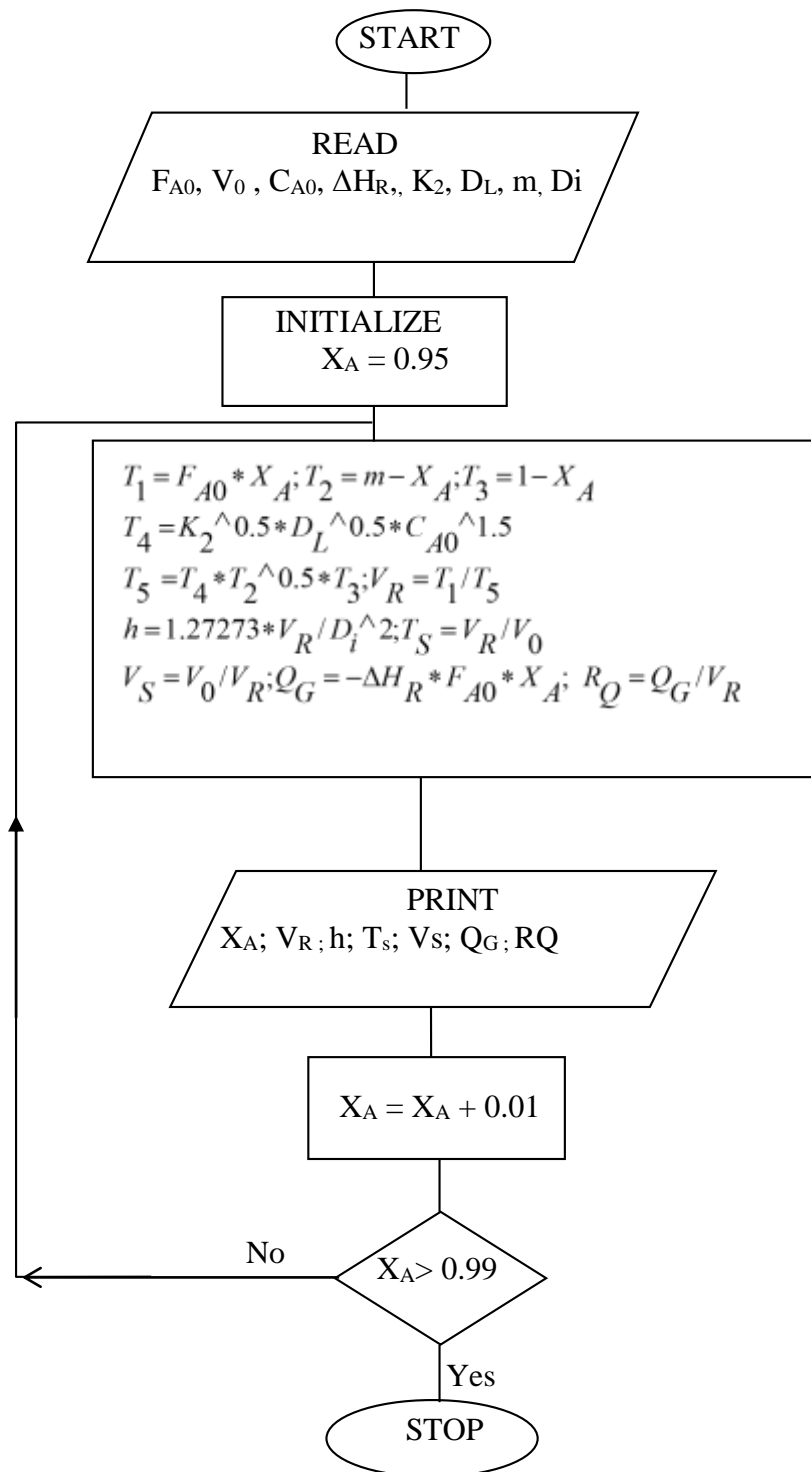
Algorithm flow chart for isothermal cast

Figure 4: Flow chart describing the computation of isothermal CSAT functional Parameters.

Input parameters evaluation
The CSAT performance models developed in section 3 contain unknown parameters such as the molar flow rate, concentration, volumetric flow rate etc. These parameters have to be determined before equations 15 - 23 can be evaluated.

Table 1 Design data sheet.

Quantity	Symbol	Value	Unit
Initial concentration of SO_2	C_{A0}	16,759	mol/m^3
Heat of reaction	ΔH_R	-88	Kj/mol
Product Density (H_2SO_4)	ρ_P	1.64×10^3	Kg/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
Molar ratio of reactants	m	1.0 - 1.5	
Radius of CSTR	R	0.025 - 0.5	m
Liquid phase diffusivity of SO_3	D_L	17	m^2/Sec
Volumetric flow rate of reactants	V_0	2.352×10^{-4}	m^3/Sec

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 1.389×10^3 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 height, 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 height as a result of sulphur trioxide addition to water with conversion degree is illustrated in figures 4, 5, 6, 7, and 8.

From the results it was observed that the reactor volume, space time, and reactor height increases with increasing degree of conversion, while the space velocity, and heat generation per reactor volume decreases with increasing degree of conversion.
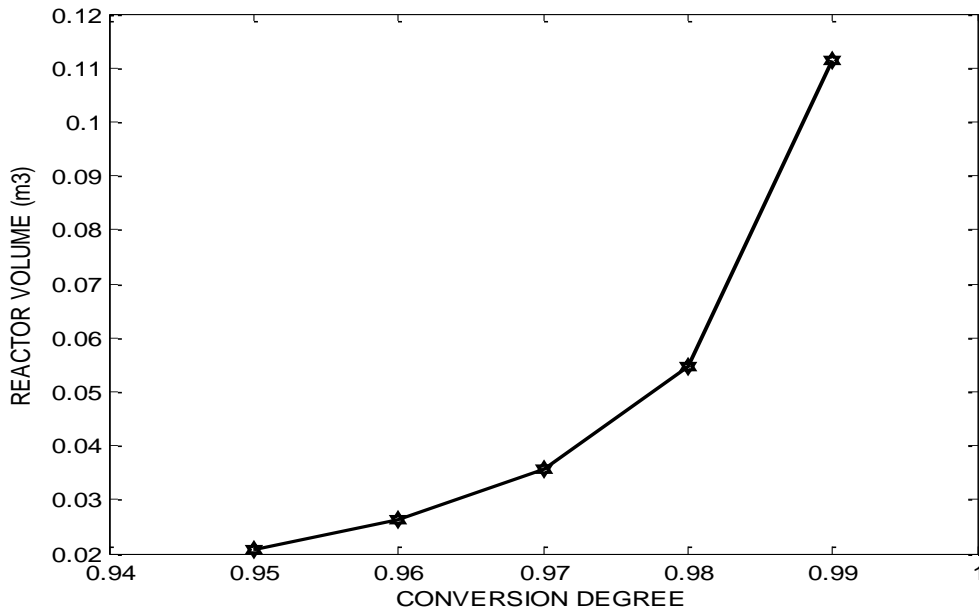
Figure 5: Plot of Reactor Volume against Conversion Degree for Isothermal CSTR
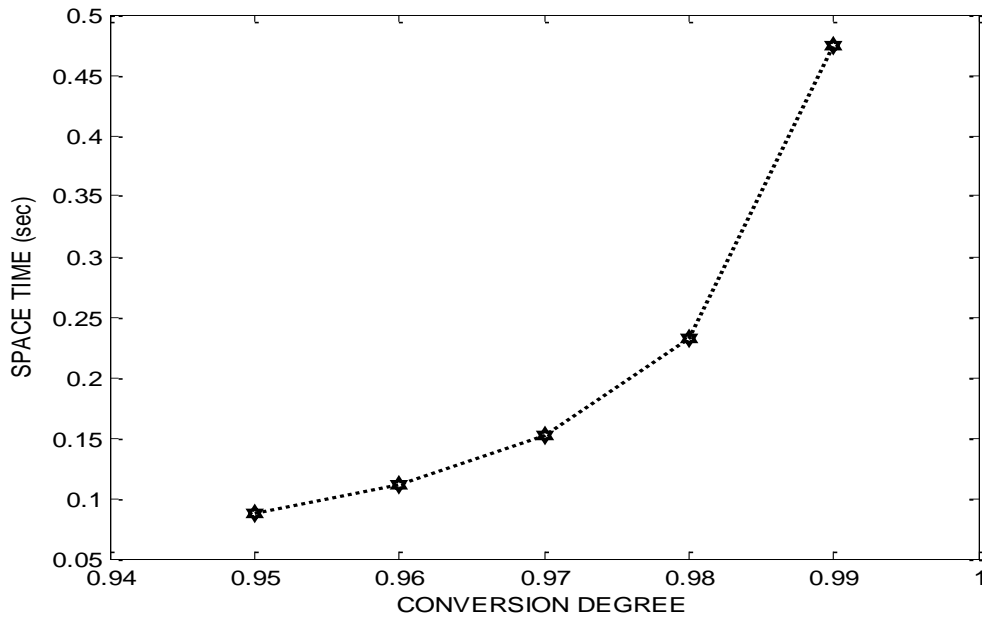

Figure 6: Plot of Space Time against Conversion Degree for Isothermal CSTR
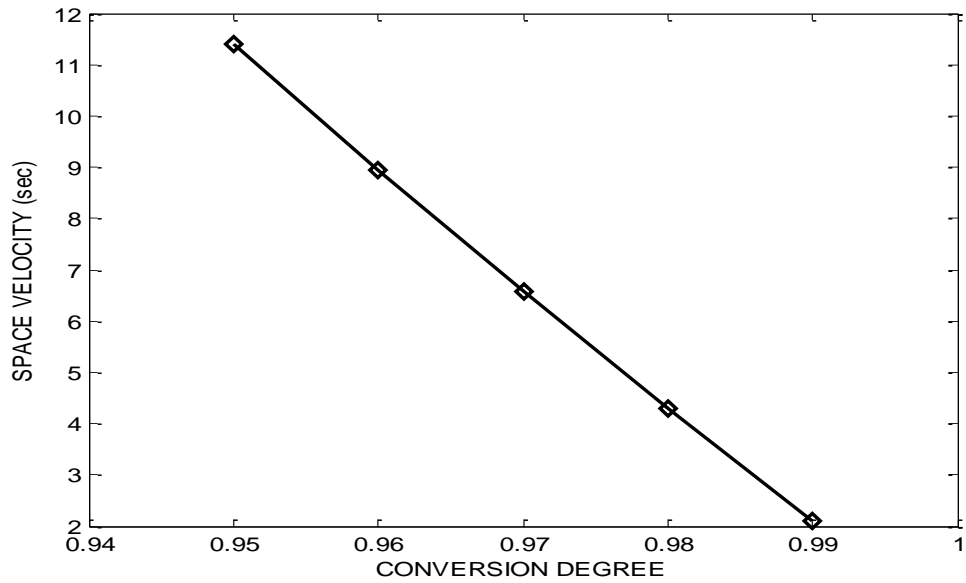
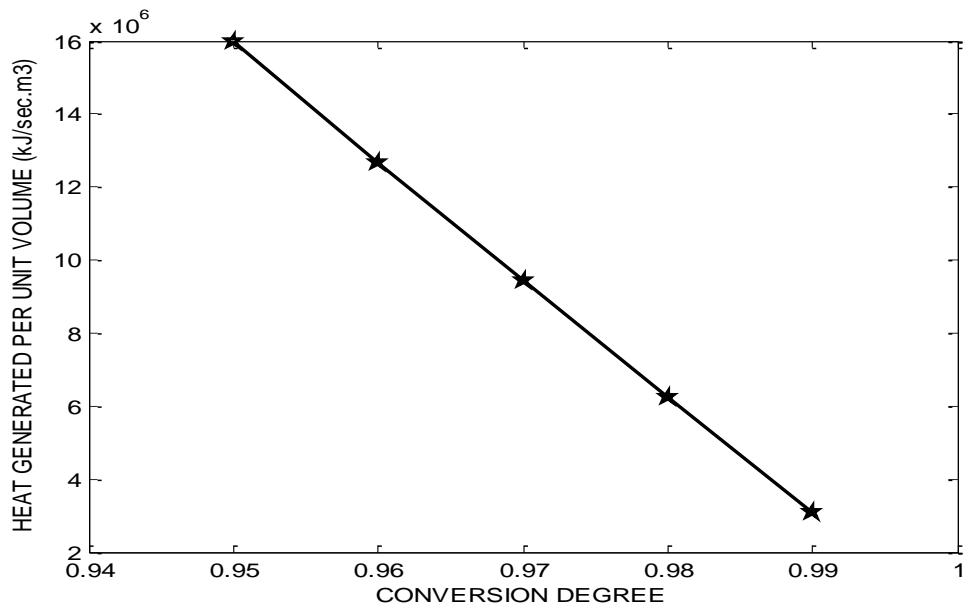*Figure 7: Plot of Space Velocity against Conversion Degree for Isothermal CSTR*

Figure 8: Plot of Heat Generated per unit Volume against Conversion Degree for Isothermal CSTR
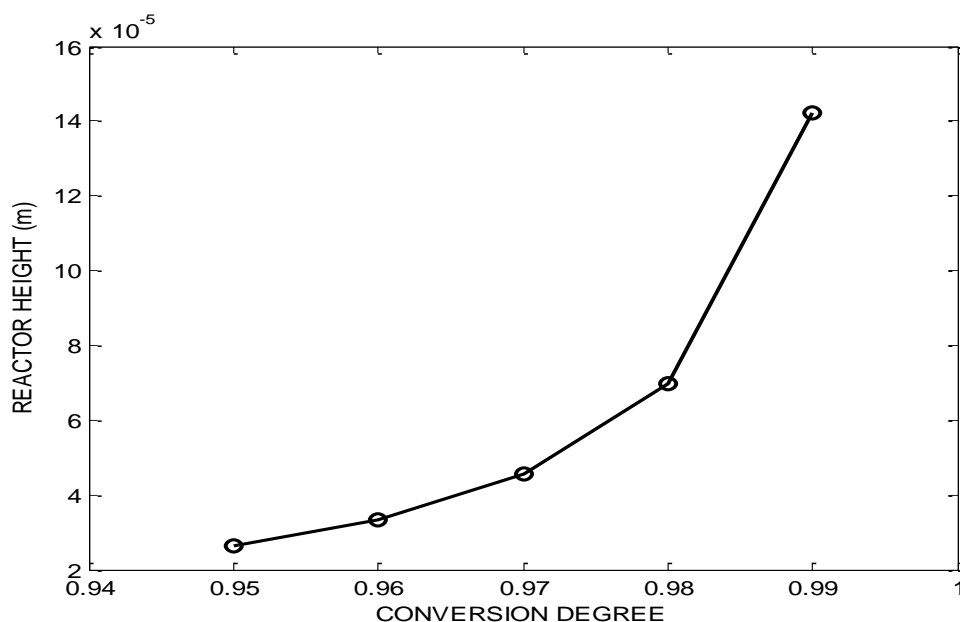
Figure 9: Plot of Reactor Height against Conversion Degree for Isothermal CSTR

From the results of the computation for the isothermal CSAT 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.

Conclusion and recommendation

An isothermal continuous stirred adsorption tower for vanadium catalyst based sulphur trioxide hydration process in the production of sulphuric have been designed. Computer program was developed and utilized to simulate the tower performance models over a range of conversion degree aimed at studying the performance functional dimensions behaviour. From the results of computation, it is clearly established that:

When the degree of conversion, X_A= 0.95, the reactor volume, V_R are 6.84E-05m^3 and 2.06E-05m^3, the space time, T_S are 0.2906sec and 8.76E-02sec, the reactor height h are 8.71E-05m and 2.62E-052m, and the rate of heat generation per reactor volume, R_Q are 4.8205E06KJ/sec.m^3 and 1.5988E07KJ/sec.m^3 for the reactant molar ratio, m=1.0 and 1.5 respectively.

When the degree of conversion, X_A=0.99, the reactor volume, V_R are 7.965E-04m^3 and 1.115E-04m^3, the space time, T_S are 3.3863sec and 0.4742sec, the reactor height, h are 1.0137E-03m and1.42E-04m, and the rate of heat generation per reactor volume, R_Q are 4.312E05KJ/sec.m^3 and 3.079E06KJ/sec.m^3 for the reactant molar ratio, m=1.0 and 1.5 respectively.

From (a) – (b) above, the reactor volume, the reactor height and the space time were greater at the upper limit of conversion degree, while the space velocity and the rate of heat generation per unit reactor volume decreases as conversion degree increases. Further work should critically concentrate on the aspects of process optimization and comparison analysis of all the sulphur trioxide hydration towers.

References
1. Abowei, M. F.N. (1989). Computer-aided design of heat exchanger for P.F. reactor in the addition of ethylene oxide. Part 1: Design equation development. *Modeling, simulation and control*, B. AMSE press, vol. 25, no. 4, pp. 15-24.

2. Abowei M.F.N and Goodhead T. O (2014) "Modelling of Non-isothermal CSTR Adsorption Tower for Sulphur Trioxide Hydration using Vanadium Catalyst" International Journal of Modern Engineering Science Florida, USA (Accepted in Press)

3. Ancheya – Juarez, J. C., A (1997. Strategy for Kinetic Parameter Estimation in the Fluid Catalytic Cracking Process, Ind. Eng. Chem. Res., 36 (12): pp 5170- 5174,.

4. Austin, G. T. (1984), Shreve's Chemical process industrial. Fifth edition, publisher   McGraw-Hill, pp370-345.

5. Blanding, F. H.(1953), Reaction Rates in Catalytic Cracking of Petroleum, Industrial and Engineering Chemistry, 45 (6) pp 1186-1197,.

6. Charles G. Hill, jr (1977), An Introduction to chemical engineering Kinetics & Reactor design, 1st edition, John Wiley & Sons USA, pp5-16, pp509-523.

7. Chenier, P. J. (1987), Survey of industrial chemistry, John Wiley & Sons, New York, pp45-47.

8. Christenson, G., Apelian, M. R., Hickey, K. J., Jaffe, S. B.(1999), Future Directions in Modeling of the FCC Process: An Emphasis on Product Quality, Chemical Engineering Science, 54:pp. 2753-2764,.

9. Corma, A., Melo, F. V., Sauvanaud,L(2005), Kinetic and Decay Cracking Model for a Micordowner unit, Applied Catalysis A: General, 287 (1): pp 34 -36,.

10. Coulson, J. M., Richardson, J. F. (1978), Chemical Engineering, vol.2, 3rd Edition, Pergamon press Inc., New York, pp.529-530, 547-550.

11. Coulson J. M., Richardson J. F.(1979) "Chemical Engineering" Vol. 3, 2nd Edition, Pergramon Press Inc. New York Pp. 3 -10, 36 -42.

12. Danner and Daubert,(1983) Manual for predicting Chemical Process design data, Alche, New York,.

13. Dewachtere, N.V., Santaella, F., Froment, G. F.(1999), Application of a single event kinetic Model in the simulation of an industrial Riser Reactor for the Catalytic Cracking of Vacuum Gas Oil, Chemical Engineering Science, 54: pp. 3653-3660,.

14. Duecker and West (1975), Manufacture of Sulphuric acid, Reinhold, New York.

15. Erikson, T. E. (1974), Chem Soc, Faraday Trans. I, 70, 203.

16. Faith, K. C. (1965), Industrial Chemistry, Third edition pp. 747 -755, John Wiley 8 Sons New York.

17. York Fair, G. M. Geyer, J.C.; and Oken D.A. (1968): *Water Purification and waste water treatment, and disposal, volume 2*. Water and waste water Engineering, New York Wiley.

18. Forment, G. F.(2001), Modeling of Catalyst Deactivation, Applied Catalysis A: General, 211 (1.2): pp. 117 – 128,.

19. Fogler, H. S. (1994) *Elements of Chemical Reaction Engineering*. 2nd edition Prentice-Hall Inc., India.

20. Gibney, S. C., and Ferracid, G. (1994) Photocatalysed Oxidation, Journal of Horganic Chemistry, Vol. 37, pp. 6120-6124.

21. Goodhead T. O and Abowei M.F.N (2014) "Design of Isothermal Plug Flow Reactor Adsorption Tower for Sulphur Trioxide Hydration using Vanadium Catalyst" International Journal of Innovative Science and Modern Engineering (IJISME), Volume 2, Issue 9, Pp9-16.

22. Goodhead T. O and Abowei M.F.N (2014) "Modelling of Semi Batch Reactor Adsorption Tower for Sulphur Trioxide Hydration using Vanadium Catalyst" International Journal of Scientific and Engineering Research, Volume 5, Issue 8.

23. Goodhead T. O and Abowei M.F.N (2014) "Modelling of Non-isothermal Plug Flow Reactor Adsorption for Sulhur Trioxide Hydration Using Vanadium Catalyst" International Journal of Technology Enhancement and Emerging Engineering Research, IJTEEE, Volume 2 Issue 9

24. Goodhead T. O and Abowei M.F.N (2014) "Modelling of Non-isothermal CSTAT for Sulphur Trioxide Hydration using Vanadium Catalyst" International Journal of Engineering and Technology UK, volume 4 issue 9 (Accepted in Press)

25. Octave Levenspiel (1999) "Chemical Reaction Engineering Third Edition" John Wiley & Sons New York Chichester Weinheim Brisbane Singapore Toronto