DEVELOPMENT OF STEADY STATE MODEL EQUATIONS FOR OPTIMIZATION OF HIGH PRESSURE CARBAMATE CONDENSER IN UREA PLANT

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ABSTRACT

The research for the development of steady state models to predict optimal yield of High Pressure Carbamate Condenser (HPCC) has been carried out. Different urea production processes were discussed and literatures related to urea production were reviewed. The Stamicarbon design for Urea production was chosen for this research. The research applies the principles of conservation of mass and energy to develop the steady state concentration and temperature models of the High Pressure Carbamate Condenser (HPCC) which was modeled as a plug flow reactor. The kinetics of the reaction was studied from the fundamentals of the chemical reaction involving Ammonia (NH₃) and carbon dioxide (CO₂) to form the intermediate product called Urea Carbamate and eventually dissociate to give Urea. The mathematical models developed were simulated using numerical 4th – order ode 45 algorithm and profile plots were obtained. The research shows how the reactants deplete to form the desired product at various points along the reactor, showing the concentrations of the intermediate and final products along the High Pressure Carbamate Condenser (HPCC). The yield of the model prediction was compared to the Urea plant values obtained from Notore Chemical Industries PLC. The yield of Urea Carbamate from the developed model gave a higher value of 46% instead of the normal plant yield of 40%, a deviation of 6%.

Keywords: Urea Carbamate, Plug Flow Reactor, High Pressure Carbamate Condenser, Ammonia, Carbon dioxide.

INTRODUCTION

Urea is an important nitrogen fertilizer made using the Harber Boch process from the reaction of carbon (iv) oxide (CO₂) and ammonia (NH₃). Its use is steadily increasing as the world's favorite nitrogen fertilizer Urea fertilizer is used as a solid fertilizer, liquid fertilizer, formaldehyde resins, apotheosis, etc.

Rouelle first discovered Urea in urine in 1773; Woehler's synthesis of ammonia and cyanic acid followed his discovery in 1828. The first synthesis of an organic compound from an inorganic compound is considered to be this. By heating ammonium carbamate in a sealed tube in which urea was first synthesized by dehydration, Bassarow produced urea in 1870, (*Kumar et al., 2007*).

NH₂CONH₂ chemical formula indicates that the amide of carbonic acid NH₂COOH or carbonic acid CO(OH)₂ can be considered as urea. Fertilizer is generally defined as "any organic or inorganic, natural or synthetic material that provides one or more of the chemical elements necessary for plant growth" (*Smith, 1988*). The fertilizer industry's main objective is to provide the primary and secondary nutrients needed in macro qualities. Chemical fertilizers normally

supply primary nutrients. Chemical reactions generally produce them. Whatever the chemical compounds may be, the nutrient content is its most important ingredients for plant growth. The primary nutrients are nitrogen, phosphorus and potassium. However, their concentration in a chemical fertilizer is expressed as a percentage of total nitrogen (N), available phosphate $[P_2O_5]$ and soluble $[K_2O]$ (*Kumar et al., 2007*). The grade of a fertilizer is expressed as a set of three numbers in the order of percent N, P₂O₅ and K₂O.

The most widely produced types of fertilizer are nitrogen-based fertilizers, accounting for 82.79 million tons produced worldwide between 2016 and 2017. Urea is the most widely produced among all nitrogen-based fertilizers, producing 37.57 million tons between 2016-2017. It is important to note that there is a significant increase in urea consumption, Jumping from 8.3 million tons in 2010 - 2011 to 37.57 million tons in 2016 - 2017, equivalent to roughly 46 percent of total global nitrogen consumption. The importance of Urea production and the availability of modern flow sheeting tools motivated Stamicarbon to apply basic thermodynamics principles and software engineering to create a tool that can be used to model the most important aspects of the processes of urea production currently being used. The Stamicarbon and Snamprogetti processes correspond to approximately 76% of the world market.

Basic principles, the commercial production of urea is based on the reaction of ammonia $[NH_3]$ and Carbon dioxide $[CO_2]$ at a high pressure and temperature to form ammonium Carbamate $[NH_2COONH_4]$, which in turn is dehydrated into urea and water.

Different technologies in the production of urea fundamentally differ in how urea is separated from reactants and how ammonia and carbon dioxide are recycled. Production technology refinements are usually focused on increasing the conversion of carbon dioxide, optimizing heat recovery, and reducing utility consumption. Various processes for the manufacture of urea are:-

- 1. Snamprogetti ammonia stripping process
- 2. Stamicarbon CO₂ stripping process
- 3. Once through urea process
- 4. Mitsui Toutsu total recycle urea process.

This project mainly takes into account the process of stripping Stamicarbon CO_2 . Urea has a wide range of uses ranging from its use in the production of solid fertilizer, the production of liquid fertilizer, the production of urea-formaldehyde (coating agent and adhesive as well), melamine-formaldehyde resins, etc.

LITERATURE REVIEW

Kumar et. al., (2007) conducted a study on the Snamprogetti design process for the production of urea and discussed how this process is based on the principle of internal carbamate recycling and is commonly referred to as the Snam NH3 removal process. The fundamental difference between the Snamprogetti process and the conventional carbamate solution recycle urea processes is that in this case, the unconverted carbamate is stripped and recovered at reactor pressure from the urea synthesis reactor effluent solution, condensed into an aqueous solution in a high-pressure carbamate condenser steam, and recycled back into the reactor by gravity. *Smith, (1988)* performed a steady state model on the Urea fertilizer plant Stamicarbon design. The novelty of the CO_2 stripping process is that the reactor effluent is not lowered as in the conventional liquid recycling urea process, but is stripped by the gaseous CO_2 reactor feed stream in a steam-heated vertical heat exchanger at synthesis pressure.

At about 140 atm and 190°C, the high pressure stripper operates. The stripped urea solution still contains about 15% of the unconverted carbamate, and for further degassing in the steam-heated low pressure decomposer or low pressure carbamate condenser (LPCC) at about 120°C, it is let down to about 3 atm. The off gas recovered is condensed with cooling water in the low pressure carbamate condenser, operating at about 65°C and 3atm. The solution thus obtained is pumped to the high pressure condenser by means of high pressure carbamate pump. The off gas recovered from the high pressure stripper is condensed in the high pressure carbamate condenser (HPCC), which operates at about 170°C and 140 atm. The condensation heat is removed by vaporizing the equivalent amount of condensate on the condenser's shell side. The resulting 3.4 atm steam can be reused in another plant section.

MATERIALS AND METHODS

Materials

To predict the performance of the high pressure carbamate condenser (HPCC), a mathematical model of the HPCC will be developed.

Assumptions

The following assumptions have been made in developing the model:

- 1. The high pressure carbamate condenser (HPCC) operates at steady state
- 2. The high pressure carbamate condenser (HPCC) is assumed to be a plug flow reactor, meaning that concentration varies along the length of the reactor

The mathematical model will be developed from first principle by applying the principle of conservation of mass and energy.

The materials in this research are the high pressure carbamate condenser (HPCC), (modeled as a plug flow reactor), thermodynamic data, literature data, principle of conservation of mass and energy, rate expressions, NH₃, Co₂ stream, coolants/H₂0, and flow rates of the liquid and gas.

Methods

The method applied here is the development of high pressure carbamate condenser (HPCC) models (assumed as plug flow reactor) using the principle of conservation of mass and energy and optimization of the reactor to achieve high yield.

Model Development

The material and energy balance principles taking place around a tubular reactor for the transient and steady state models for heat and partial pressure are developed as thus:



$$P_{T} A\Delta l \Delta y_{i} = P_{T} A u_{f} \Delta \tau y_{i,l}^{\tau} - P_{T} A u_{f} \Delta \tau y_{i,l+\Delta l}^{\tau+\Delta \tau} - (-r_{i}) A \Delta \tau \Delta l$$
(1)

$$P_{T} A\Delta l \Delta y_{i} = -P_{T} A u_{f} \Delta \tau \left[y_{i,l+\Delta l}^{\tau+\Delta \tau} - y_{i,l}^{\tau} \right] - (-r_{i}) A \Delta \tau \Delta l$$
(2)

$$P_{T}A\Delta l \frac{\Delta y_{i}}{\Delta \tau} = -(P_{T}Au_{f}\Delta \tau) \underline{\Delta \gamma}_{i} - (-r_{i})A\Delta \tau \Delta l$$
(3)

Divide equation (3) by $P_TA\Delta l\Delta \tau$

$$\frac{\Delta y_i}{\Delta \tau} = -u_f \frac{\Delta y_i}{\Delta l} - \frac{\left(-r_i\right)}{P_T} \tag{4}$$

$$\operatorname{Lim} \frac{\Delta y_i}{\Delta \tau} = \frac{\partial y_i}{\partial \tau}; \quad \operatorname{Lim} \quad \frac{\Delta y_i}{\Delta l} = \frac{\partial y_i}{\partial l}$$
(5)

Substituting equation (5) into (4) yields;

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$$\frac{\partial y_i}{\partial \tau} = -uf \frac{\partial y_i}{\partial l} - \frac{\left(-r_i\right)}{P_T}$$
(6)

At steady – state; $\frac{\partial y_i}{\partial \tau} = 0$; equation (6) becomes:

$$=> \qquad \frac{dy_i}{dl} = -\frac{\left(-r_i\right)}{P_T \mu_f} \tag{7}$$

Equation (7) is the steady state mole fraction model of tubular reactor.

Equation (7) is the steady state mole fraction model of tubular reactor.

Energy Balance

 $\rho C \rho A \Delta l \Delta T i = \rho_i, C \rho A u_f \Delta \tau T_{i,l}^{\tau} - \rho_i, C \rho A u_f \Delta \tau T_{i,c+\Delta t}^{\tau+\Delta \tau} - (-r_i) A \Delta l \Delta \tau (-\Delta H_{r,i}) - Q \Delta \tau \Delta l$ Taking fluid to be incompressible with properties that $\rho C p = \rho_i C p_i = \rho_i C p_i = \text{constant throughout; then:}$ $\rho C_P A \Delta \tau \Delta T_i = \rho_i, C \rho A u_f \Delta \tau \Big[T_{i,c+\Delta t}^{\tau+\Delta \tau} - T_{i,l}^{\tau} \Big] - \Big(-\Delta H_{r,i} \Big) \Big(-r_i \Big) - \dot{Q} \Delta \tau \Delta l$ (9)

Divide all through by $\rho C \rho \Delta \tau \Delta l$

$$\frac{\Delta T\iota}{\Delta \tau} = -u_f \left[\frac{\left[T_{i,c+\Delta i}^{\tau+\Delta \tau} - T_{i,l}^{\tau} \right]}{\Delta l} - \frac{\left(-\Delta H_{r,i} \right) \left(-r_i \right)}{\rho C_P} - \frac{\dot{Q}}{\rho C_P A} \right]$$
(10)

$$\frac{\Delta T_i}{\Delta \tau} = -u_f \frac{\Delta T}{\Delta \iota} - j(-r_i) - \frac{Q}{\rho C_P}$$
(11)

Where
$$j = \frac{\left(-\Delta H r_i\right)}{\rho C_P}, \quad j = Q / A \quad (KW/m^2)$$
 (12)

$$\operatorname{Lim} \Delta \tau \to 0 \quad \frac{\Delta T}{\Delta \tau} = \frac{\partial T_{i}}{\partial \tau} \quad \operatorname{lim} \Delta \tau \to 0 \quad \frac{\Delta T_{i}}{\Delta \iota} = \frac{\partial T_{i}}{\Delta \tau} = -\frac{\partial T_{i}}{\partial \tau}$$
(13)

$$\frac{\partial T_i}{\partial \tau} = u_f \frac{\partial T_i}{\partial \tau} - j(-r_i) - \frac{q}{\rho C_P}$$
(14)

At steady state;
$$\frac{\partial \tau}{\partial \tau} = 0$$

Thus: $O = -u_f \frac{dT_i}{d\tau} - j(-r_i) - \omega$ (15)
 $\frac{dT_i}{d\tau} = i(-r_i) - \omega$

$$\Rightarrow \frac{dH}{dl} = -\frac{j}{u_f} (-r_i) - \frac{\omega}{u_f}$$

$$\frac{dTi}{dl} = a (-r_i) + b$$
(16)
Where $a = -\frac{j}{u_f} (m^2.s. \text{ K. Kg-1}); b = -\frac{w}{u_f} (\text{K}).$

Equation (16) is the model equations of the temperature for steady state.



Optimization of the Reactor

A $\xrightarrow{k_1} B \xrightarrow{K_3} C$ Condition for more of Urea Carbamate formation, the forward reaction constants is far greater them backward reaction constants. $k_f \gg k_2$; $k_3 \gg k_4$. Where $k_1 = k_f$ for the 1st reaction; $k_f = k_3$, $k_f = k_3$ for second reaction. $(-r_{CO2}) = k_f P_T y_{CO2}$ Let $C_{O_2} = A$ $-\frac{\kappa}{\kappa} \rightarrow -\frac{\kappa}{\kappa} \rightarrow$ $P_A = CO_2$ For B = Intermediate (Urea Carbonate) C = UreaThe rate expressions for the various species give: $(-r_A) = \frac{dC_A}{dt} = K_1 C_A$ (17)But $dt = \frac{dz}{u_f}$ (18)Where, u_f = superficial velocity $\frac{\frac{-dC_A}{dz}}{u_f} = K_1 C_A$ (19) $\frac{-dC_A}{dz} = \frac{K_1}{u_f} C_A$ (20)Integrating equation (3.37) $\int_{C_{AO}}^{C_A} \frac{dC_A}{c_A} = \frac{-K_1}{u_f} \int_0^z dz$ $In \frac{C_A}{C_{AO}} = \frac{-K_1}{u_f} z$ $C_A = C_{AO} e^{-K_1/u_f z}$ (21)For species B, the rate expression gives: $r_B = \frac{dC_B}{dt} = K_1 C_A - K_3 C_B$ $u_f \frac{dC_B}{dz} = K_1 C_A - K_3 C_B$ Divide all through by u_f (22) $\frac{dC_B}{dz} + \frac{K_3 C_B}{u_f} = \frac{K_1}{u_f} C_{AO} e^{-K_1/u_f Z}$ Where $a = \frac{K_1}{u_f}$; $b = \frac{K_3}{u_f}$ $\frac{dC_B}{dz} + bC_B = aC_{AO}e^{-az}$ Using integrating factor; $IF = e^{bz}$ $e^{bz}\left\{\frac{dC_B}{dz} + bC_B\right\} = e^{bz}K_1C_{AO}e^{-az}$ $\int \frac{d}{dz} \{e^{bz} C_B\} d_{C_B} = K_1 C_{AO} \int e^{bz} e^{-az} dz$ $e^{bz}C_B = K_1 C_{AO} \int e^{(b-a)} dz$ $e^{bz}C_B = \frac{K_1C_{AO}}{b-a}e^{(b-a)z} + C$ (23)

Boundary Conditions $at z = 0; C_B = C_{BO} = 0:$

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$$0 = \frac{k_{1}C_{AO}}{b-a}e^{(b-a)0} + C$$

$$\Rightarrow C = -\left(\frac{k_{1}C_{AO}}{b-a}\right)$$
(24)
Putting equation (24) into (23) gives Urea Carbamate formation as:
$$C_{B} = \left(\frac{k_{1}C_{AO}}{b-a}\right)e^{(b-a)z}e^{-bz} - \left(\frac{k_{1}C_{AO}}{b-a}\right)e^{-bz}$$

$$C_{B} = \frac{k_{1}C_{AO}}{b-a}e^{-az} - \frac{k_{1}C_{AO}}{b-a}e^{-bz}$$
(25)
For species C:
$$(r_{C}) = \frac{dC_{C}}{dt} = K_{3}C_{B}$$
(26)
$$u_{f} \frac{dC_{C}}{dz} = k_{3}C_{B}$$
(26)
$$u_{f} \frac{dC_{C}}{dz} = k_{3}C_{B}$$
(27)
But $C_{AO} = C_{A} + C_{B} + C_{C}$

$$\Rightarrow C_{C} = C_{AO} - C_{AO}e^{-az} - \left(\frac{k_{1}C_{AO}}{b-a}\right)\{e^{-az} - e^{-bz}\}$$
(28)
$$= C_{AO}\left\{1 - e^{-az} - \frac{k_{1}}{b-a}(e^{-az} - e^{-bz})\right\}$$
(29)

$$= \frac{b-a}{b-a} \left\{ b + K_1 e^{-bz} + a e^{-az} - b e^{-az} - K_1 e^{-az} \right\}$$

$$= \frac{c_{AO}}{b-a} \left\{ b + K_1 e^{-bz} + a e^{-az} - b e^{-az} - K_1 e^{-az} \right\}$$
(20)

$$C_C = \frac{C_{AO}}{b-a} \{ b(1-e^{-bz}) - a(1-e^{-az}) + K_1(e^{-bz} - e^{-az}) \}$$
(30)

Equations (21), (25) and (30) shows the concentrations of the limiting reactant (CO_2), Urea Carbamate and Urea respectively.

Solution Techniques

The models equations developed are solved using Ode 45 numerical integration techniques build in MATLAB.

RESULTS

The mathematical models developed to predict the performance of the High Pressure Carbamate Condenser (HPCC) in terms of the concentrations of CO_2 which is the limiting reactant (C_A), Urea Carbamate (C_B), Urea (C_C), Partial pressure of CO_2 and temperature at steady state are resolved and simulated numerically using 4th order Runge Kutta algorithm. The various plots and tables were obtained and the yield of optimal Urea Carbamate calculated as shown below:

Z	Ca	Cb	Cc
0	0.364	0	0
2	0.338717	0.009673	0.0634
4	0.315189	0.017342	0.123728
6	0.293296	0.023329	0.181013
8	0.272924	0.027909	0.23531
10	0.253967	0.031317	0.286689
12	0.236326	0.033752	0.335235
14	0.219911	0.035383	0.381044
16	0.204636	0.036353	0.424218



Figure 1: Concentrations of CO_2 (C_A), Urea Carbamate (C_B) and Urea (C_C) along the HPCC Reactor.

Figure 1 shows the concentration profile of CO_2 (C_A), Urea Carbamate (C_B) and Urea (C_C) along the length of the HPCC Reactor. The graph clearly shows how the limiting reactant CO_2 depletes along the HPCC as Urea Carbamate and Urea is formed.

From the graph, the concentration of CO_2 drops from 36.4% to 20.46% indicating the of CO_2 consumption. It is important to note that the concentration of CO_2 will not drop to zero (0)

because about 1/5 of the feed is needed to react in the main reactor to produce the required heat necessary to produce the heat for the endothermic reaction. The trends of the model results obtained from this work are similar to Notore plant data for both the exothermic reaction in the High Pressure Carbamate Condenser (C_B) yielding Urea Carbamate and the endothermic reaction in the main Urea Reactor (C_C) yielding Urea.

Table 2:	Validation of Steady State Results with Plant Data				
S/N	PARAMETERS	PLANT DATA	MODEL	%	
			RESULT	DEVIATION	
1	Partial Pressure (KPa)	14000	14185.49968	0.007	
2	Mole fraction (mole)	0.02	0.012357	38	
3	Temperature (k)	463	462.9997985	0.000044	
4	Yield (%)	40	46	6	

Table 2 shows that the deviation between the model prediction and the industrial plant output with respect to the yield was 6%.

CONCLUSIONS

A first principle approach was adopted in developing the model equations used in the analysis of the High Pressure Carbamate Condenser (HPCC) under study. HPCC equipment is modeled as a tubular reactor (Plug flow reactor).

The principles of conservation of mass and energy were applied on the reactor and steady state models for the concentrations of CO_2 , Urea Carbamate, Urea, partial pressure and temperature were developed. The rate supervisions for the conversion of Ammonia and Carbon dioxide from different chambers into the HPCC to get Urea at 46% were developed in terms of the limiting reagents (carbon dioxide).

The models were resolved numerically using 4th order Runge-Kutta and finite difference approximations respectively for steady state models of CO₂, Urea Carbamate, Urea concentrations, Partial Pressure and Temperature.

Data from **Notore** chemical industries PLC - a chemical industry that produces urea and other nitrogenous fertilizer, located in Onne, Rivers State, Nigeria were obtained and used in solving the mathematical model equations. The result obtained from solutions to the models were compared with the output plant data at 100% load, and a maximum deviation between outputs from solved models and actual plant data was obtained as 6%.

The results and discussion agrees with the research objectives as upgrade of 6% yield from the normal 40% the plant usually produced to 46% yield obtained from the modeling work shows that the procedures for this work and aim are met.

If the simulation is applied, a higher percentage of urea will be converted with lesser energy consumption as compared to the energy consumed in practice especially during product concentration stages (1st and 2nd evaporation) to yield the desired 99.8% of urea required.

To maximize profit (maximum product yield), optimum operating conditions which will result in the maximum performance of the High Pressure Carbamate Condenser (HPCC) should be chosen. Such optimum conditions were obtained from the optimization of the reactor. Therefore, the mathematical model and computer simulation carried out in this project showed that modeling is a very useful technique/tool which can be applied industrially to predict the performance of reactors hence, maximize yields of product and minimize wastage.

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The following recommendations are made for the research work to be adopted

- The modeling work should be recommended and applied to Fertilizer Company to upgrade the first stage of production of Urea from HPCC.
- The Rate expression of this research should be useful and recommended to the Urea fertilizer company as it is the driving force of the production process.

REFERENCES

- Bernardis, M., Carvoli, G., & Santini, M. (2009). Urea–NH₃–CO₂–H₂O: VLE Calculations using an Extended UNIQUAC Equation. *Fluid Phase Equilibria*, *53*, 207.
- Chen, H. S., & Stadtherr, M. A. (1985a). Simultaneous-Modular Approach to Process Flowsheeting and Optimization. Part I. Theory and Implementation. *American Institute* of Chemical Engineering Journal, 31, 1843.
- Chen, H. S., & Stadtherr, M. A. (1985b). Simultaneous-Modular Approach to Process Flowsheeting and Optimization. Part II. Performance on Simulation Problems. *American Institute of Chemical Engineering Journal*, 31, 1857.
- Chen, H. S., & Stadtherr, M. A. (1985c). Simultaneous-Modular Approach to Process Flowsheeting and Optimisation. Part III. Performance on Optimization Problems. *American Institute of Chemical Engineering Journal*, 31, 1868.
- Dente, M., Pierucci, S., Sogaro, A., Carloni, G., & Rigolli, E. (1988). Simulation Program for urea plants. *Computers and Chemical Engineering*, *12*, 389.
- Dente, M., Rovaglio, M., Bozzano, G., & Sogaro, A. (1992). Gas-liquid reactor in the Synthesis of Urea. *Chemical Engineering Science*, 47, 2475.
- Irazoqui, H. A., & Isla, M. A. (2013). Simulation of Urea Synthesis Reactor. 2. Reactor Model. Industrial and Engineering Chemistry Research, 32, 2671.
- Isla, M. A., Irazoqui, H. A., & Genoud, C. M. (2010). Simulation of Urea Synthesis Reactor. Thermodynamic Framework. *Industrial and* Mei, A. H. (1994). *Handbook of Ammonia Synthesis Technology Design*.
- Joshi M V. Process Equipment Design, 3rd Edition. New delhi: Mcmillan India Limited, 2001.
- Kellogg, M. K. (2008). Notore Chemical Industries Urea Plant Handbook and Data Sheet, Vol 2.
- Kumar, B., & Pratap, C. D. (2007). Manufacture of Urea. National Institute of Technology, Rourkela.
- Nakamura, R. C., Bread, V. J. F., & Prausnitz, J. M. (1975). Thermodynamic Representation of Gas Mixtures Containing Common Polar and Nonpolar Components. *Industrial and Engineering Chemistry, Product Research and Development*, 15, 557.
- Sander, B., Rasmussen, P., & Fredenslund, A. (1986). Calculation of Solid–Liquid Equilibria in Aqueous Solutions of Nitrate Salts using an Extended UNIQUAC Equation. *Chemical Engineering Science*, 41, 1197.
- Satyro, M. A., Li, Y. K., Agarwal, R. K., & Santollani, O. J. (2001). Modeling Urea Processes: A New Thermodynamic Model and Software Integration Paradigm. <u>http://www.cheresources.com</u>.
- Shreeve R N. Chemical Process Industries, 3rd Edition. New York: McGraw Hill Book Company, 1996

Progressive Academic Publishing, UK

Stamicarbon (1985). The know-how people, urea. London, UK: Parnell House.

- Wei, S. A. (1994). *Research and Development on Urea Simulation System (in Chinese)*. Doctoral Dissertation. Dalian University of Technology.
- Westerberg, A. W., Hutchinson, H. P., Motard, R. L., & Winter, P. (1979). *Process Flowsheeting*. Cambridge: Cambridge University Press.
- Yuan, Y., & Wang, W. S. (2009). *Fertilizer Engineering Series: Urea*. Beijing: Chemical Industry Press (in Chinese).
- Zhang, X. P., Chen, H. S., Li, Y. K., Liu, X. Y., Yao, P. J., & Yuan, Y. (2002). Simulation of Urea Reactor. *Journal of Dalian University of Technology*, *41*, 653 (in Chinese).
- Zhang, X. P., Yao, P. J., Wu, D., & Yuan, Y. (2005). Simulation of Urea Reactor of Industry. Computational Methods in Multiphase, Series: Advances in Mechanics, 29(65), 110 -120.
- Zhang, X. P., Zhang, S. J., & Yao, P. J. (2007). Simulation of Highpressure Urea Synthesis Loop. In *The 47th Annual Safety in Ammonia Plants and Related Facilities Symposium*.