A New Suggested Adaptive Controller for Multivariable Nonlinear System.

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Abstract— The present paper introduces the mathematical model of urea plant and suggests two methods for designing special purpose controllers. The first proposed method is PID controller and the second is sliding mode controller (SMC). These controllers are applied for a multivariable nonlinear system as a Urea Reactor system. The main target of the designed controllers is to reduce the disturbance of NH3 pump and CO2 compressor in order to reduce the pollution effect in such chemical plant. Simulation results of the suggested PID controller are compared with that of the SMC controller. Comparative analysis proves the effectiveness of the suggested SMC controller than the PID controller according to disturbance minimization as well as dynamic response. Also, the paper presents the results of applying SMC, while maximizing the production of the urea by maximizing the NH3 flow rate. This controller kept the reactor temperature, the reactor pressure, and NH3/CO2 ratio in the suitable operating range. Moreover, the suggested SMC when compared with other controllers in the literature shows great success in maximizing the production of urea.

Index Terms— Sliding mode controller, PID controller, urea reactor, Process Control, Chemical Industry, Adaptive controller, Nonlinearity.

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1. Introduction

Urea synthesis is one of the most important industries in agriculture as a fertilizer [1-2]. Urea is generally used as a crude material in producing many chemical compounds including chemical solutions, plastics, adhesives and medical drugs. Urea is a natural compound in chemical equation CO(NH2)2. In 1828, WOHLER discovered that urea can be produced from ammonia and cyanic acid in water solution. Since then, research on the urea preparation has continuously progressed [2-3].

In 1907, urea was produced on a limited industrial scale by dehydration of Cyanamid, which was obtained from calcium Cyanamid:

$$CaCN_2 + H_2O + CO_2 \longleftrightarrow CaCO_3 + CNNH_2 \qquad (1)$$

$$CNNH_2 + H_2O \longleftrightarrow CO\,(NH_2)_2 \qquad (2)$$
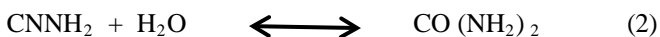
The first point for the industrial production of urea is the lab synthesis of BASAROFF [4], in which urea is obtained by dehydration of ammonium carbamate at increased pressure and temperature, the principle response happens in the fluid stage under pressure running from 13 to 25MPa. While, the reactor temperature is from 170 to 200∘C [5-10].
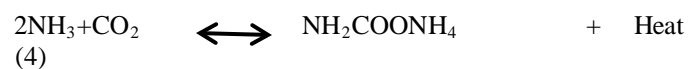
In the literature these are two suggested operation of reactors. The first operation was proposed by Frejacques [8] which is the originally seniority kinetic models for Urea reactor. The reaction is describes as shown in equ. (3).
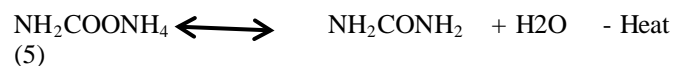
$$2NH_3 + CO_2 \longleftrightarrow NH_2COONH_2 \qquad (3)$$
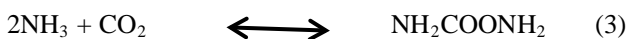
In Equ (3), the reaction between NH3 and CO2 takes place under 145 bars pressure in order to form Urea. The urea is produced in one step reaction by reacting ammonia and carbon dioxide.

The second operation was generally accepted among researchers up to1952.in this operation the urea is produced in two step reaction: first by reacting ammonia (NH3) and carbon dioxide (CO2), in gaseous phase, at high temperature (170 – 200°C), and high pressure (13 – 25 Mpa) (130 - 250 bars) in presence of ammonia carbamate (NH2COONH4) saturated solution in which the carbamate, in liquid phase is formed. This reaction is exothermic and fast. In the second reaction, which is endothermic and slow, the ammonium carbamate dehydrates to produce water (H2O) and urea (NH2CONH2) [10-15]. The reactions are described as:

a- Condensation reaction

$$2NH_3 + CO_2 \longleftrightarrow NH_2COONH_4 \qquad + \text{Heat} \qquad (4)$$

b- Dehydration reaction

$$NH_2COONH_4 \longleftrightarrow NH_2CONH_2 + H2O \qquad - \text{Heat} \qquad (5)$$

The reactor is composed such that its volume is sufficiently enormous for the wanted urea generation. The condensation reaction is the first reaction that takes place in urea plant. The condensation is depending on Pressure of condensation, reactor temperature, molar ratio between ammonia and carbon dioxide (NH3/CO2 ratio) and the molar ratio between water and carbon dioxide (H2O/CO2 ratio). The urea conversion increases when increasing temperature and

NH3/CO2 ratio. To achieve the maximum urea conversion and reduce the pollution effect, the molar ratio between ammonia and carbon dioxide must be equal 3. The block diagram of urea synthesis process is shown in Fig.1. There are five stages for Urea synthesis plant. Synthesis stage, Recirculation stage, Desorption and Hydrolyzation Stage, Evaporation stage, and Granulation stage.
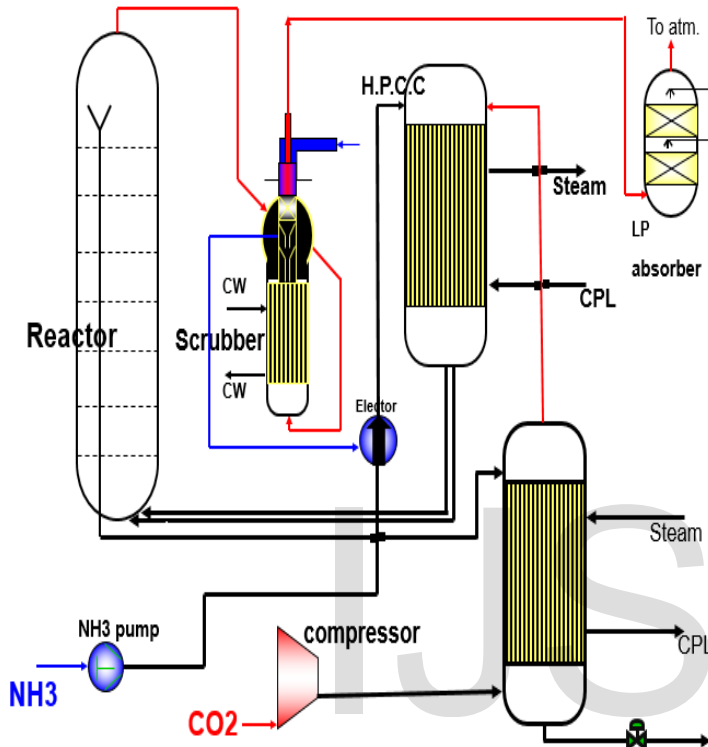

Fig.1. Block diagram of Urea synthesis process.

1- Synthesis Stage:

In which condensation reaction between NH3 and CO2 takes place under (140-146) bars pressure in order to form ammonium carbamate inside high pressure carbamate condenser (H.P.C.C). After that carbamate molecule loses water molecule and turns into urea molecule inside the reactor. The synthesis pressure consists of four equipment's working under high pressure about 145 bars High Pressure Carbamate Condenser (H.P.C.C), Reactor, High Pressure Stripper, and High Pressure Scrubber.

H.P.C.C:

In which the first reaction between NH3 and CO2 both in gas phase takes place to form ammonium carbamate. This reaction is exothermic so in order to happen and continue heat produced from the reaction should be withdrawn. Heat is withdrawn by the production of low pressure steam about 4 bars. The equipment is a heat exchanger (shell and tube). The reaction happens inside the tubes and steam is produced in the shell side. Reaction between NH3 and CO2 gases doesn't happen in a complete form so a part of these gases should be

left to go to the reactor in the gas phase to react inside it. Carbamate in the liquid and gas phases flow to the reactor.

Reactor

Reactor is a vertical cylindrical equipment. It contains a number of perforated sieve trays to allow gases to flow through perforations and liquid to flow through the distance between the wall and the tray. The liquid and gas phases' carbamate goes into reactor bottom out of the H.P.C.C and the gases reaction takes place first for the production of urea. Urea goes out of the reactor with about 35% concentration heading to the stripper. The reacted gases from reactor and inert gases goes to the scrubber.

H.P Scrubber

The outlet reactor gases is washed by the means of low concentration carbamate solution from recirculation stage for the absorption of NH3 and CO2.

High Pressure Stripper:

Urea solution outlet reactor with concentration of about 35% goes to the stripper top. The rest is carbamate so it should be restored and directed again to the H.P.C.C. At the same time urea solution is concentrated from 35% to 57%. The stripping process is achieved by the counter current flow of CO2 gas from its compressor.

Medium pressure steam (about 20 bars) is directed to the stripper shell side for the decomposition of carbamate and stripping it from urea solution using CO2. Decomposed and stripped gases out solution of urea goes out of the stripper top with the CO2 heading to the H.P.C.C. Urea solution comes out stripper bottom after it is concentrated to about 57% heading to recirculation stage with low pressure (about 4 bars) for completing urea concentration process.

2- Recirculation Stage:

After urea solution flows out of the stripper with concentration of about 57% the solution is flashed from 140 bars to 4 bars. In which the urea solution temperature is raised to get rid of NH3 and CO2 and increase urea solution to about 72%. Separated gases out of the solution head from rectifying column to the low pressure carbamate condenser (L.P.C.C).

3- Desorption and Hydrolyzation Stage:

The desorption idea is based on the stripping of NH3 gas from diluted solution of about 5% NH3-water using low pressure steam (about 4 bars). After ammonia gas is separated from ammonia water it flows to the reflux condenser where it is condensed and recycled into process again. The operation of hydrolyser is the same as the reactor but reversed. In which urea is hydrolyzed by means of 24 bars steam to its primary components NH3 and CO2. After that the outlet gases from

the hydrolyser goes to the reflux condenser to be recycled into the process again.

4- Evaporation Stage:

In the evaporation stage urea solution is concentrated from about 72% to 96%. The process takes place in tow equipment's pre-evaporator and evaporator. Evaporation process takes place at 100°c in the pre-evaporator and 132°c in the evaporator and under vacuum about 0.3 bar abs and the process happens under these circumstances to reduce urea hydrolysis and biuret formation.

5- Granulation Stage:

Urea fertilizer granules are produced through the injection of 96% concentration urea melt into the granulator on a bed of urea fine granules inside it. The basic idea is to fluidize the fertilizer with air and it can be briefed as follows:-

1- First urea solution is concentrated through evaporators and transformed from liquid to melt with 96% concentration.
2- Urea melt is injected on a bed of urea fine granules where the melt is pushed with pressurized air called atomization air through small nozzles, urea melt sprays out the nozzles to accumulate on the fine granules of the bed where urea granules are shaped in the desired size.

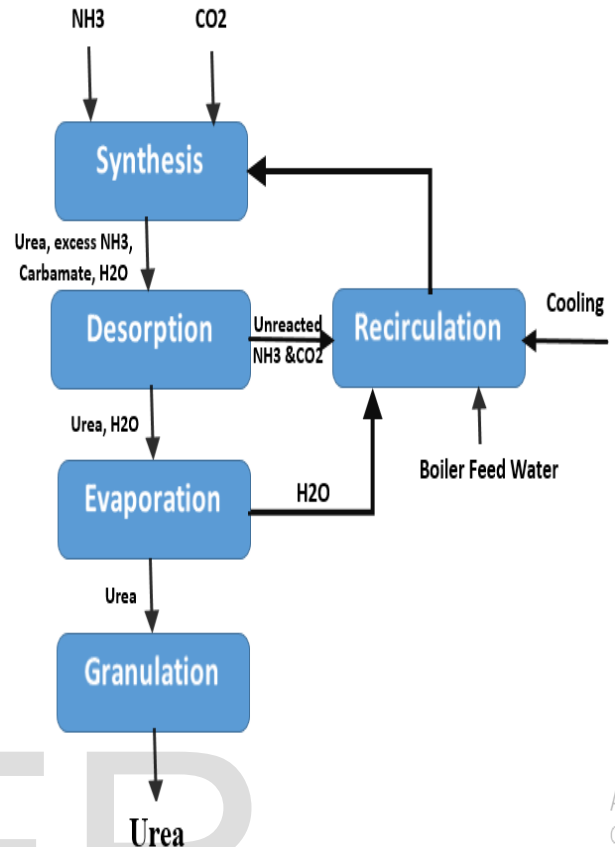The flow chart of urea synthesis process is shown in Fig. 2.

Fig.2. Flow chart of Urea synthesis process.

2. Mathematical model of urea reactor

Equations (4) and (5) will be converted as €1 and €2 while the overall conversion as €1 * €2 = €.

$$\text{€}1 = \frac{F_C + F_U}{F_{Ci} + F_{Di} + F_{Ui}} \qquad (6)$$

$$\text{€}2 = \frac{F_U}{F_C + F_U} \qquad (7)$$

$$\text{€} = \text{€}1 * \text{€}2 = \frac{F_U}{F_{Ci} + F_{Di} + F_{Ui}} \qquad (8)$$

Where, F_U, F_C and F_D are the flow rates of urea, carbamate and Carbone dioxide respectively. F_{Ci}, F_{Di} and F_{Ui}, are the initial flow rate of urea, carbamate and carbon dioxide respectively.

The flow rates of urea F_U, carbamate F_C, carbon dioxide F_D, ammonia F_N, water F_H and total rate F_T which is the sum of all individual flow rate are represented as:

$$F_U = \text{€} * (F_{Ci} + F_{Di} + F_{Ui}) \qquad (9)$$

$$F_C = (\text{€}1 - \text{€}) * (F_{Ci} + F_{Di} + F_{Ui}) \qquad (10)$$

$$F_D = (1 - €1) * (F_{Ci} + F_{Di} + F_{Ui}) \quad (11)$$

$$F_N = (a - 2€1) * (F_{Ci} + F_{Di} + F_{Ui}) \quad (12)$$

$$F_H = (b + €) * (F_{Ci} + F_{Di} + F_{Ui}) \quad (13)$$

$$F_T = (1 + a + b + € - 2 * €1) \quad (14)$$

Where a and b, are ammonia and water feed ratios which are represented as:

$$a = \frac{F_{Ni}}{F_{Ci} + F_{Di} + F_{Ui}} \quad (15)$$

$$b = \frac{F_{Hi}}{F_{Ci} + F_{Di} + F_{Ui}} \quad (16)$$

The rate of reactions for Co2, NH3 and Urea are represented as:

$$r_{Co2} = -k_{1F} * (Cd * Cn^2 - \frac{Cc}{k_1}) \quad (17)$$

$$r_{Carb} = k_{1F} * \left(Cd * Cn^2 - \frac{Cc}{k_1}\right) - k_{2F} * (Cc - Cu * \frac{Cw}{k_2}) \quad (18)$$

$$r_{Urea} = k_{2F} * (Cc - Cu \frac{Cw}{k_2}) \quad (19)$$

Where, k_{1F} and k_{2F} are kinetic for the forward two urea reactions equations, Cd, Cc, Cu are molar flow rates for carbon dioxide, carbamate and urea, k_1 and k_2 are equilibrium constants.

$$k_i = k_0 * e^{\frac{-Ea}{R * T}} \quad (20)$$

Saturated vapor pressure is represented by Clausius-Clapeyron

$$\ln p_{NH3}^s = -25.07T^{-1} + 56.321 \ln T - 0.2625T + 1.753 * 10^{-4}T^{-2} - 258.139 \quad (21)$$

$$\ln p_{Co2}^s = -2370.26T^{-1} - 0.591 \ln T - 1.178 * 10^{-2}T + 1.598 * 10^{-5}T^2 + 15.272 \quad (22)$$

$$\ln p_{H2O}^s = -5231.82T^{-1} - 6.167 * 10^{-2} \ln T - 3.291 * 10^{-3}T + 1.222 * 10^{-6}T^2 + 13.183 \quad (23)$$

The temperature must be in range 293 – 405 K in order to the equation (21) is true but in range 216 – 304 K for equation (22).

This paper presents the simulation results and analysis for the suggested control techniques for controlling the urea reactor system, applying SMC for increasing production, reducing the pollution effect and improving stability. In this paper, two design methods are suggested to minimize and reject any disturbance applied to NH3 Pump and CO2 compressor. The two methods are suggested to achieve the maximum feeding flows of NH3 and CO2. This goal will be keeping the molar ratio between ammonia and carbon dioxide equal 3 to reduce the unreacted NH3 and Co2, and increasing the urea production, the temperature of reactor and pressure of reactor in operating ranges. The first method is based on PID controller techniques. We have two PID controllers to minimize the disturbance of NH3 pump and CO2 compressor. In the first PID controller, when the urea system is subjected to disturbance due to flow rate of NH3, the reactor suffers from flow rate of NH3 oscillations. The PID controller tries to minimize and reject any internal or external disturbance by adjusting the NH3 pump. The second PID controller is used to minimized and reduce any disturbance due to flow rate of CO2 by adjusting the CO2 compressor. The second method is using SMC for NH3 pump and CO2 compressor. This paper arranged as the following. Section 2 represent the mathematical model of urea synthesis reactor. Section 3 describe the suggested method PID controller. Section 4 describe the suggested methods SMC. Section 5 describe how to using SMC to maximize the production and reducing the pollution effect by maximizing the feeding flows. Section 6 presents the simulation results obtained from the urea synthesis reactor. Then, a comparison analysis between two methods and then, a comparison analysis with previously related work.

3. A SUGGEST PID CONTROLLER FOR REDUCING SYSTEM POLLUTION.

The PID controller block diagram is shown in fig.3.1. PID controller used to remove any disturbances of NH3 Pump and CO2 compressor in Urea system. The controller uses the error signal e to produce a control signal u to control the flow through the NH3 pump and CO2 compressor [16-17]. The output control signal u(t) is described by

$$u(t) = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dt} \right)$$

Or,

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

Where, K_p is the proportional gain, T_i is the integral time, T_d is the derivative time, e(t) is the error signal, K_i is the integral gain, and K_d is derivative gain.
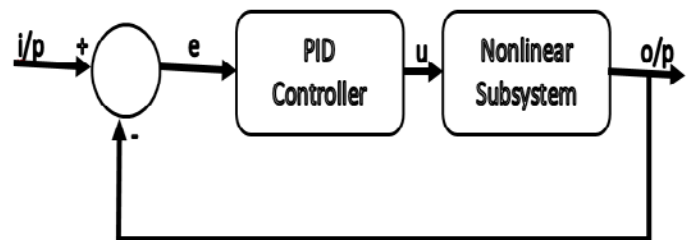

Fig.3.1. the PID block diagram.

4. A suggest sliding mode controller for reducing system pollution

The SMC has long known as a particularly suitable method for nonlinear systems with disturbances. The principle perfect of sliding mode control may be on implement the movement of the sliding mode on predefined switching surfaces in the framework state space utilizing spasmodic control. Those discontinues surfaces or those exchanging pronouncement if make chosen such-and-such sliding movement might show wanted Progress for movement done understanding with specific execution paradigm. Those strategies of the classical control theory, for example, eigenvalue placement alternately Linear-quadratic controller (LQR) to straight systems, camwood make relevant will pick fitting exchanging surfaces. Then, the discontinuous control needs to be chosen such that any states outside of the discontinuity surface are enforced to reach the surface in finite time. Accordingly, sliding mode happens along those surface, and the framework takes after those fancied framework flow [18]. The SMC block diagram is shown in fig.3.

To design the SMC, two stages are defined. The first stage is define a sliding surface of the process dynamics. The second stage is to design a feedback control law such any process's trajectory outside the sliding surface is driven to reach the surface is a finite time and keep on it. The control u(x, t) with its respective entry $u_i(x, t)$ has the form

$$u_i = \begin{cases} u_i^+ & if \quad s_i(x) > 0 \\ u_i^- & if \quad s_i(x) < 0 \end{cases}$$

Where, $s_i(x)$ switching functions, u_i^+ and u_i^- are continuous functions. Since $s_i(x)=0$ is called a switching surface.

The state trajectory under the reaching condition is satisfied which is called reaching mode [19].

Existing of sliding mode:
Reaching Condition
$$\dot{S} < -\sigma \quad sgn\,(s), \qquad \sigma > 0$$
Where, σ is positive constant.

Sliding condition

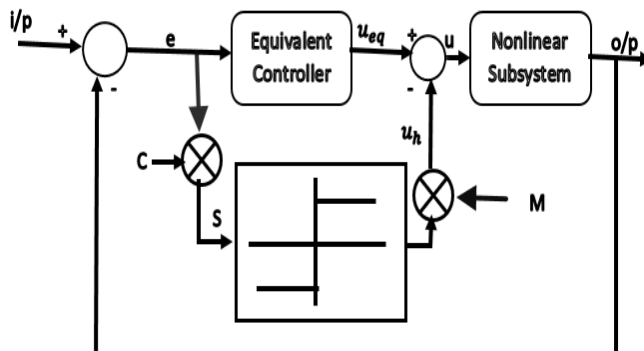$$\lim_{S \to 0^+} \dot{s} < 0, \qquad \lim_{S \to 0^-} \dot{s} > 0$$

Fig.3.2. the block diagram of SMC.

The equivalent controller is responsible for generating the u_{eq} for controlling the NH3 pump and CO2 compressor. While u_h is the hitting control signal. The constant M is used to adjust the signal to be in range 0.5 to 1. The constant c is used for amplifying the error. So it should be more than unity, and not large for reducing the chattering effect.

5. A technique for increasing urea production and reducing pollution.

A SMC is used to increasing the urea production and reducing the pollution effect. This goal is achieved by maximizing the flow rates of NH3 and CO2 while keeping the NH3/CO2 ratio to reducing the unreacted NH3 and CO2 to reduce the pollution effect. Also, the reactor pressure and temperature keeping in operating range. We have three SMCs, the first one used to control the flow rate of NH3, the second is used to control the CO2 flow rate to keep the optimal NH3/CO2 ratio, and the last one is used to reducing the reactor pressure and temperature disturbances to keeping in operating range. The urea production can be set by selecting the set point of the flow rate of NH3 controller. The NH3 flow rate multiply by a constant to produce the setpoint of CO2 flow rate. The function of CO2 flow rate controller is to keep the NH3/CO2 ratio by increased the CO2 flow rate. The amount of urea produced will be increased when augmented the setpoint of the NH3 flow rate controller.

6. Simulation results..

When the system is subjected to disturbances for NH3 Pump and CO2 compressor, the reactor suffers from NH3 and CO2 oscillations. The PID and SMCs tries to remove the disturbances in NH3 Pump and CO2 compressor. The molar ratio between ammonia and carbon dioxide must be equal three.
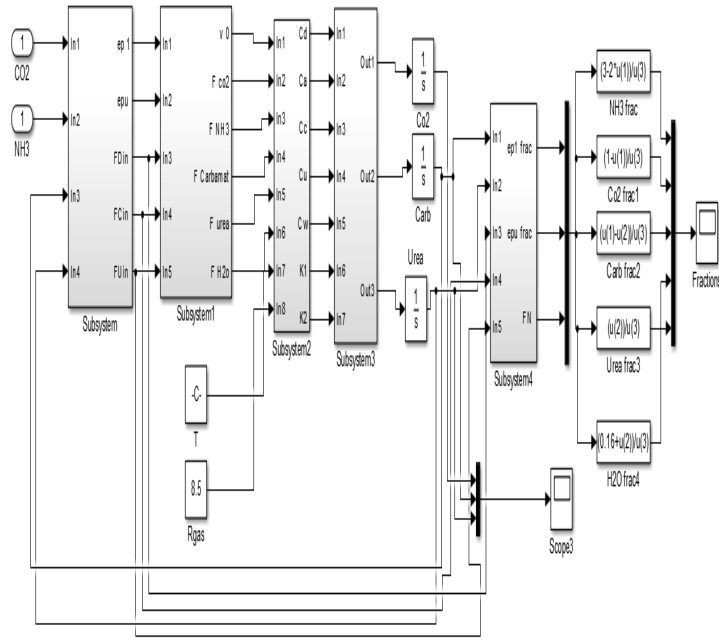
Nm3

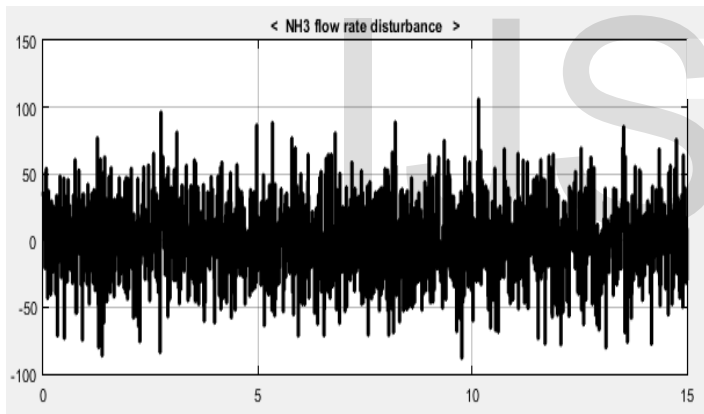Fig.4. Simulink block diagram of the urea reactor model.
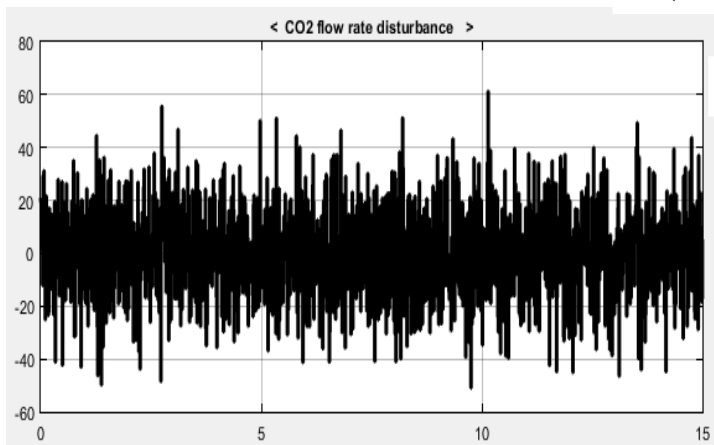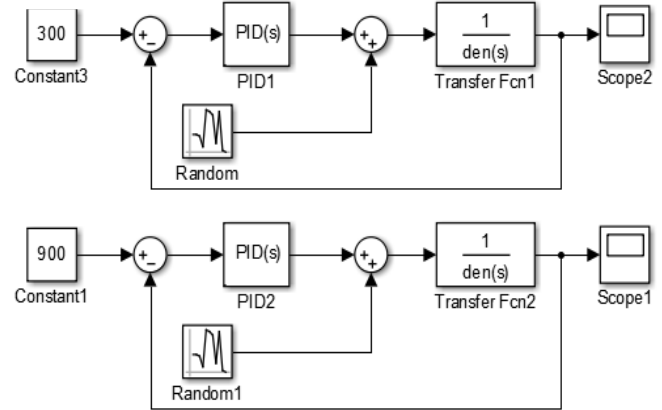
Fig.7. Simulink block diagram of the suggested PID controller.

The Simulink block diagram of the urea reactor model shown in fig.4. The disturbance of NH3 pump is shown in fig.5. Also, for CO2 Compressor is shown in fig.6. For the proposed PID controller shown in fig.7. It has proportional gain K_p as 2.33, the integral gain K_i as 6.67, and the derivative gain K_d as -0.048. The proposed controllers were suggested ted in simulation using the matlab Simulink toolbox.

Nm3

Fig.5. NH3 flow rate disturbance.

T(Sec)

Nm3

Fig.8. NH3 pump output driven by PID controller.

T(Sec)

Fig.6. CO2 flow rate disturbance.
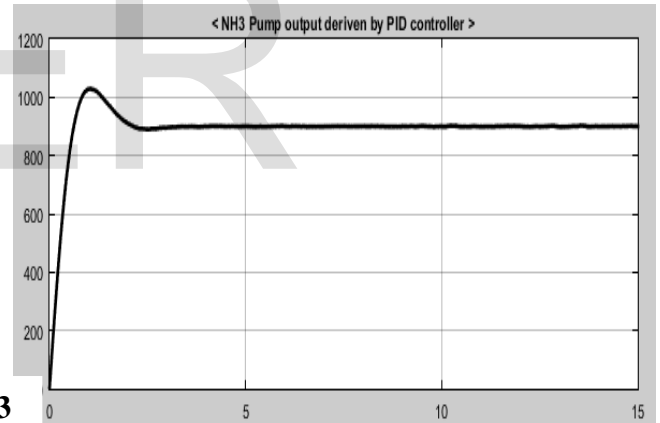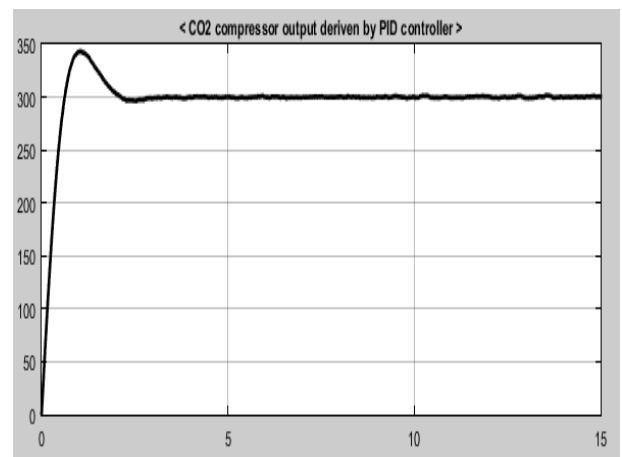
T(Sec)

Fig.9. CO2 compressor output driven by

T(Sec)
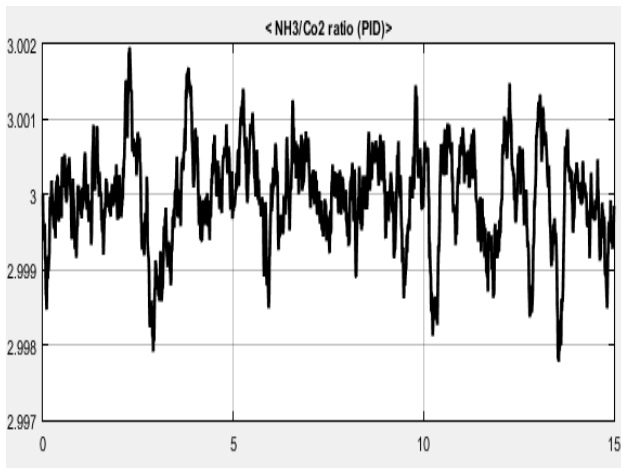
PID controller.

Fig.10. NH3/CO2 ratio curve driven by
a PID controller.
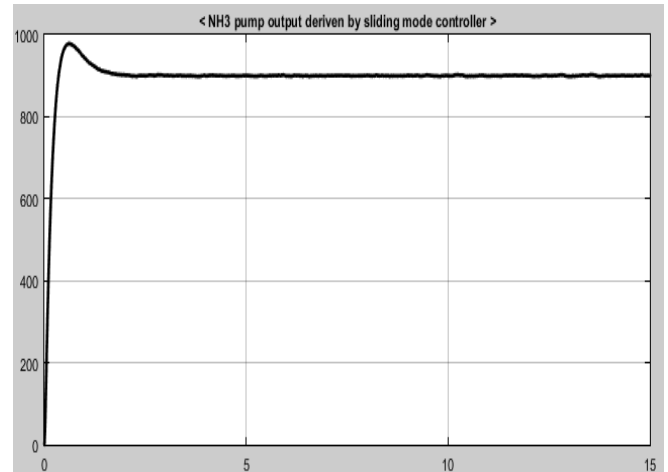
Nm3   Dynamic characteristic values. For the proposed PID controller. It has delay time as 0.243s, the rise time as 0.47s, the peak time as 1.02s, the overshoot percentage as 14.3%, and the settling time as 2.9s, NH3 flow rate is shown in fig.8. CO2 flow rate is shown in fig.9. The NH3/CO2 ratio is shown in fig.10.
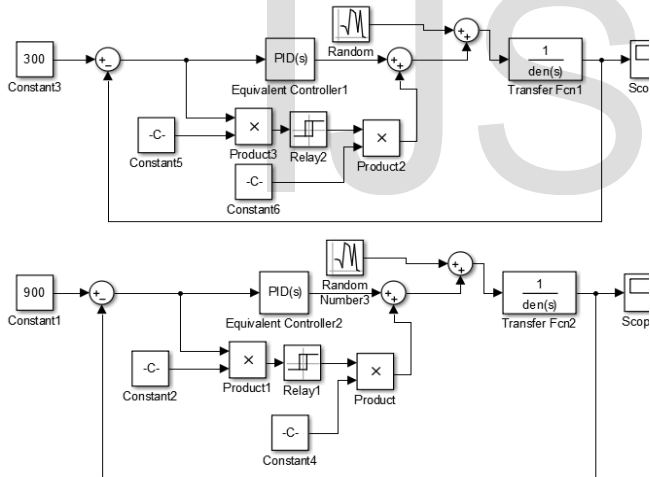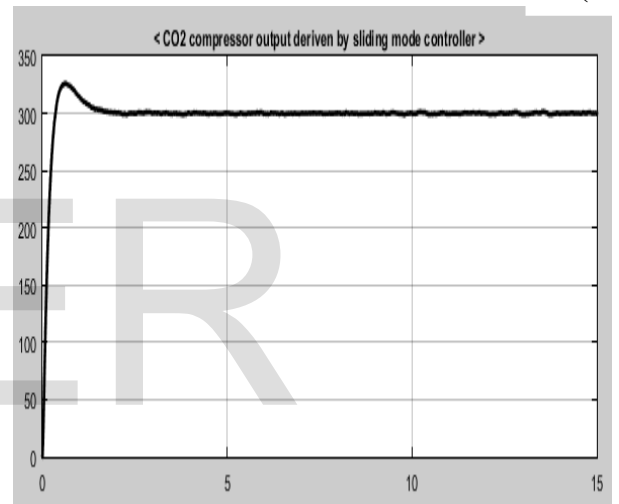

Fig.11. Simulink block diagram of the suggested SMC.

Nm3

Fig.12. NH3 pump output driven
by PID controller.   **T(Sec)**

T(Sec)

Fig.13. CO2 compressor output driven
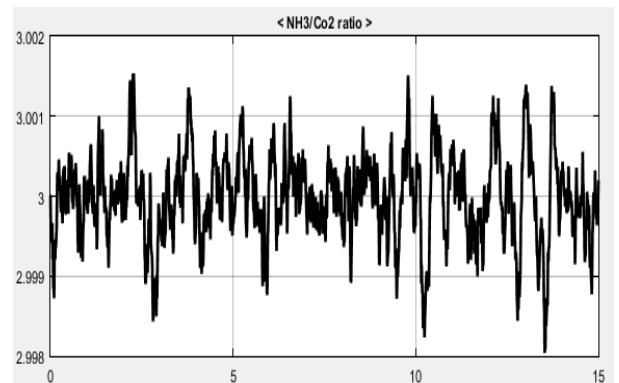by SMC.   **T(Sec)**

Fig.14. NH3/CO2 ratio curve driven by a SMC.   **T(Se**
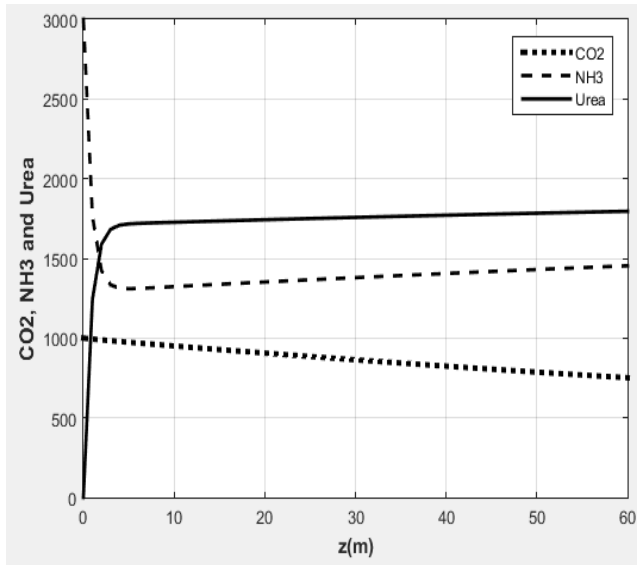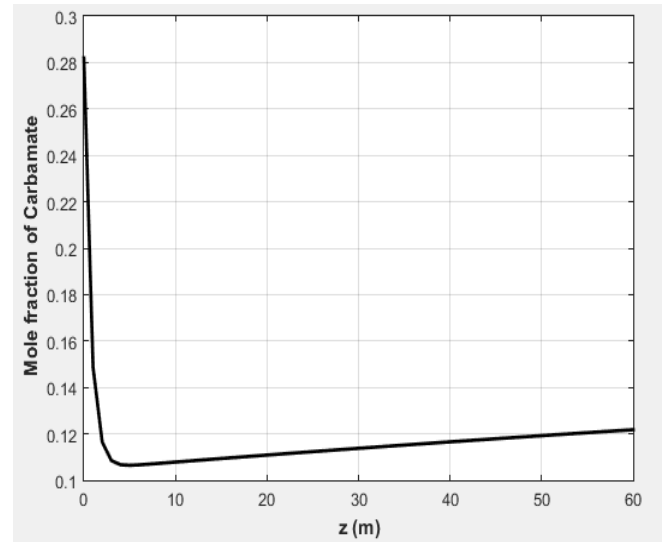
Fig. 15. Urea, NH3 and CO2 Flow Rates

Fig.17. Mole fraction of carbamate.

For the sliding mode shown in fig.11. It has delay time as 0.1148s, the rise time as 0.24s, the peak time as 0.6s, the overshoot percentage as 8.6%, and the settling time as 1.86s, NH3 flow rate is shown in fig.12. CO2 flow rate is shown in fig.13. The NH3/CO2 ratio is shown in fig.14. The Urea, NH3 and CO2 Flow Rates shown in fig.15.

	PID	Sliding mode
Delay time	0.243s	0.1148s
Rise time	0.47s	0.24s
Peak time	1.02s	0.6s
Overshoot percentage	14.3%	8.6%
Settling time	2.9s	1.86s

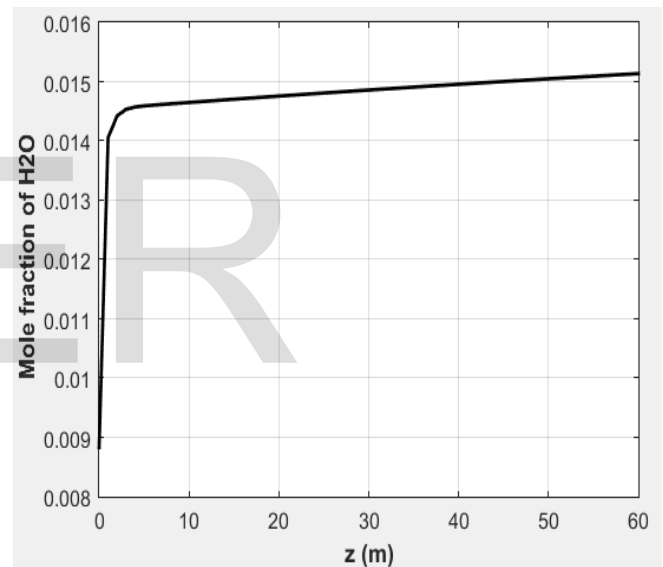Table 1. Comparative analysis between dynamic characteristic of PID and SMCs.
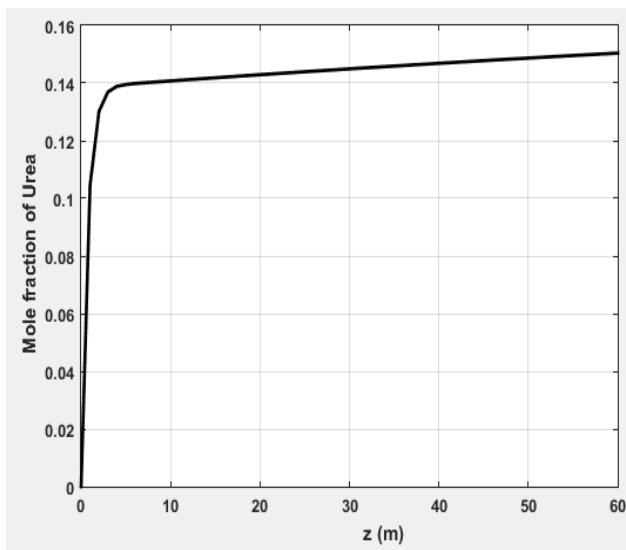

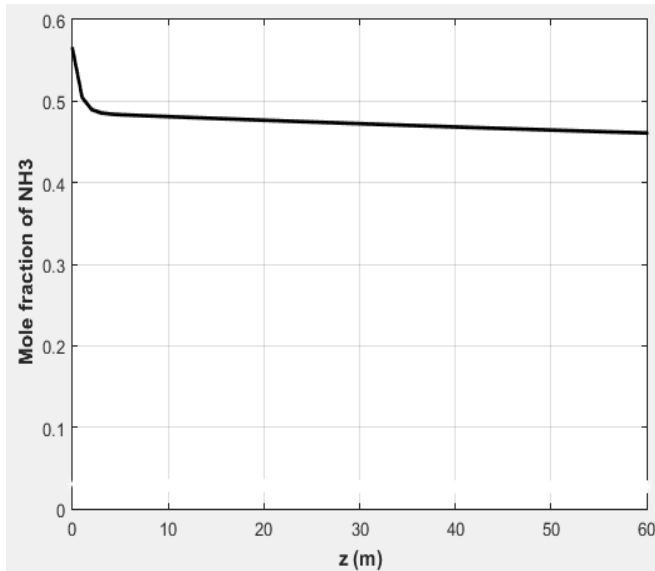Fig.18. Mole fraction of H_2O.

Fig.16. Mole fraction of urea.

Fig.19. Mole fraction of NH3.
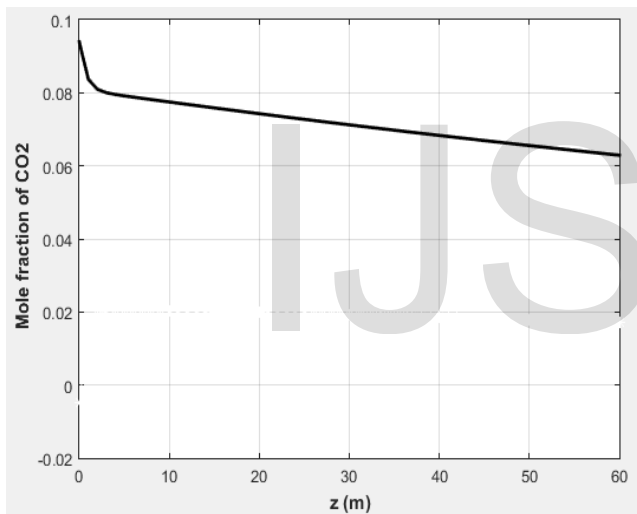

Ton/hr

Fig.20. Mole fraction of CO2

Fig.21 .NH3 flow rate.

T(hr)

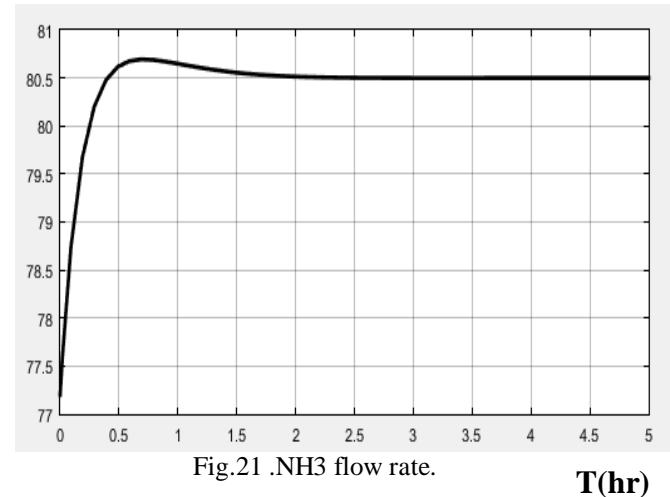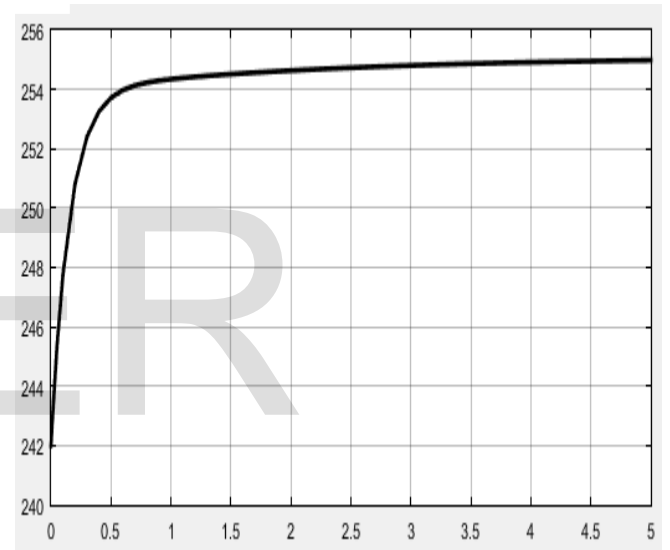**Ton/hr**

Fig.22 .Urea solution flow rate.

T(hr

All previous results is shown in table 1. The mole fractions of urea, carbamate, H2O, NH3, and Co2 are shown in Figs (16- 20). Finally, the proposed SMC is better choice to enhance the NH3/CO2 ratio as well as the PID proposed. Also, the simulation of applying SMC to maximize the production of urea are represented. The setpoints of the reactor temperature, reactor pressure and NH3/CO2 were kept on 182 °C, 145 bar and 3 respectively. When the setpoint which NH3 flow rate added equal 3.5, the NH3 flow rate was changed from 77 ton/hr to 80.5 ton/hr. the flow rate of NH3 changed by SMC is shown in fig.21. The new production of urea was **C°** from 242 ton/hr to 255.01 ton/hr. The increment of the urea production is shown in fig.22.

Ton/hr

We have obtained an increment of 13.01 ton/hr of urea when increased the flow rate of NH3 from (77 to 80.5 ton/hr). The controlled variables (reactor temperature, reactor pressure, and NH3/CO2 ratio) are kept close to their setpoints. The reactor temperature is shown in Fig.23. The reactor pressure is shown in fig.24. Also, the NH3/CO2 ratio is shown in fig.25. So the settling time for the reactor temperature is 2.55 hr, for the reactor pressure is 2.56 hr, and for the NH3/CO2 is 2.55 hr. The maximum peak for the reactor temperature is 0.202 °C, for the reactor pressure is0.155 bar, and for the NH3/CO2 is 0.004.
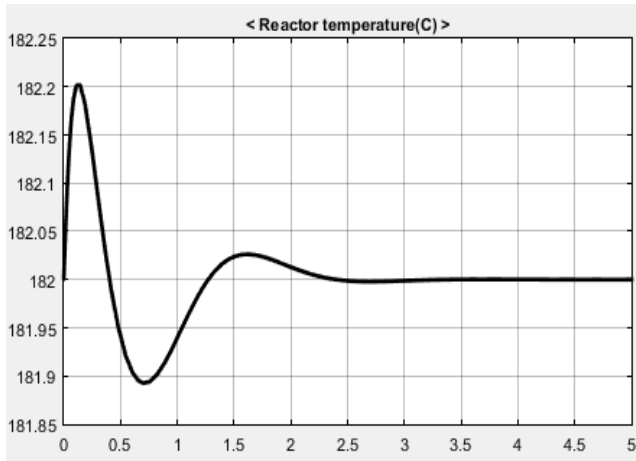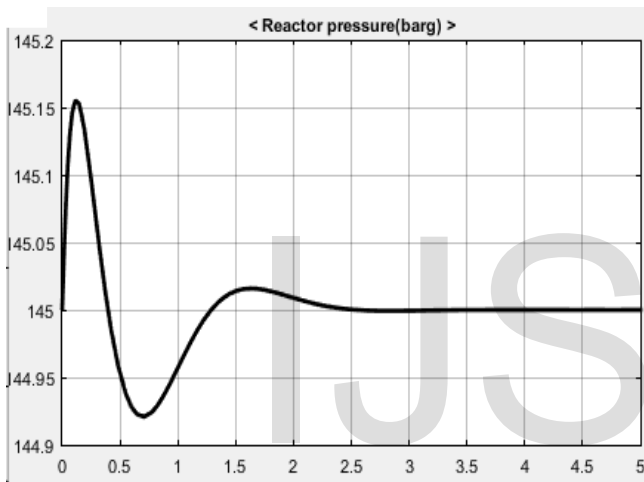
Fig.23 . Reactor temperature.

T(hr)

bar

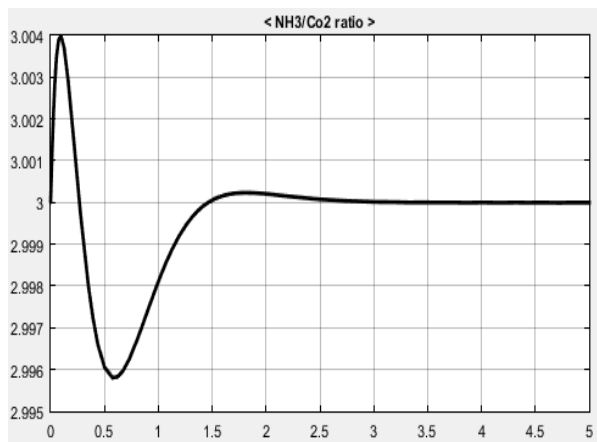

Fig.24 .Reactor pressure.

T(hr)

Fig .25 NH3/CO2 ratio.

T(hr)

7. A comparative analysis with literature.

Since SMC is effective that PID a comparison analysis between SMC and literature. For O. M. Agudelo et al. [12], presented a model predictive control (MPC) to maximize the production. It is assumed that increase the NH3 flow rate from

72.2 ton/hr to 80.5 ton/hr. the new production of urea was increased from (241.82 to 253.63) ton/hr. it is obtained an increment of 11.81 ton/hr. in the production of urea. Also the settling time for the reactor temperature is 14 hr, for the reactor pressure is 10 hr, and for the NH3/CO2 is about 14hr, The maximum peak for the reactor temperature is 0.3°C , for the reactor pressure is 0.88 bar , and for the NH3/CO2 is 0.0053.[12].

Table 2. Presents comparison analysis between proposed SMC and O. M. Agudelo et al.

		O. M. Agudelo et al.	Proposed SMC
Urea incremented		11.81ton/hr	13.01ton/hr
Maximum peak	Reactor temperature	0.3°C	0.202 °C
	Reactor pressure	0.88 bar	0.155 bar
	NH3/CO2 ratio	0.0053	0.004
Settling time	Reactor temperature	about 14hr	2.55 hr
	Reactor pressure	about 11hr	2.56 hr
	NH3/CO2 ratio	about 14hr	2.55 hr

Table2: Comparative analysis with previously related work

From table 2 the proposed SMC is better to increasing the production of urea, reducing the pollution effect, improving stability, and kept the variable (reactor temperature, reactor pressure, and NH3/CO2 ratio) on setpoints as well as the O. M. Agudelo et al [12].

8. Conclusion

The kinetic model for urea synthesis reactor in industrial scale was developed and simulation by matlab Simulink toolbox in the present paper. A modified approach for a SMC is suggested to minimize the NH3 pump and CO2 compressor disturbances in order to reduce the pollution effect in such urea reactor and reduce the unreacted NH3 and CO2, and a PI controller was tested to compare with the sliding mode one. Also, the SMC was used to increasing the production of urea, reducing the pollution effect, and improving stability. This controller kept the reactor temperature under control and also the reactor pressure, and the NH3/CO2 ratio. The results of this controller were great and very good of increment the production of urea. The increment of the production of urea was limited by the maximum feeding flow capacity usually limited by the CO2 compressor.

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