BILINGUAL PUBLISHING CO.
Pioneer of Global Academics Since 1984

Non–Metallic Material Science
https://ojs.bilpublishing.com/index.php/nmms

ARTICLE

Fluid Mechanics and Heat-Transfer Operations Combination Involved in Urea Unit of Fertilizer Complex

Muhammad Imran Rashid[1*] **Naveed Ramzan**[2]

1. Department of Chemical, Polymer and Composite Material Engineering, University of Engineering and Technology (UET)-KSK Campus, Lahore, Pakistan
2. Department of Chemical Engineering, University of Engineering and Technology, Lahore, Pakistan

ARTICLE INFO

Article history
Received: 18 February2019
Accepted: 10 March 2019
Published Online: 30 April 2019

Keywords:
Fertilizer plants
Fertilizer complex
Fluid mechanics
Heat-transfer
Urea

ABSTRACT

Fertilizer plants are most complex plants in the world (Rashid et al., 2013, Process Safety Progress) and its good opportunity to learn science from operations involved in these plants. Fluid mechanics and heat transfer operations combination involved in fertilizer complexes are explored in this article.

1. Introduction

Fertilizer plants are most complex[1]. Different accidents in fertilizer complexes such as West Fertilizer Company (2013)[2], Coffeyville Fertilizer Plant (2010)[3] and Toulouse Fertilizer complex (2001)[4] highlight significance and attention required by these complexes. Due to these accidents it's important to study fertilizer complexes more thoroughly and fluid mechanics and heat transfer operations are key of fertilizer complexes.

2. Urea Unit Overall Process

Urea unit overall process flow block diagram is shown in Figure 1. Urea unit overall process description is provided at end of article (Section 3.0) before conclusions.

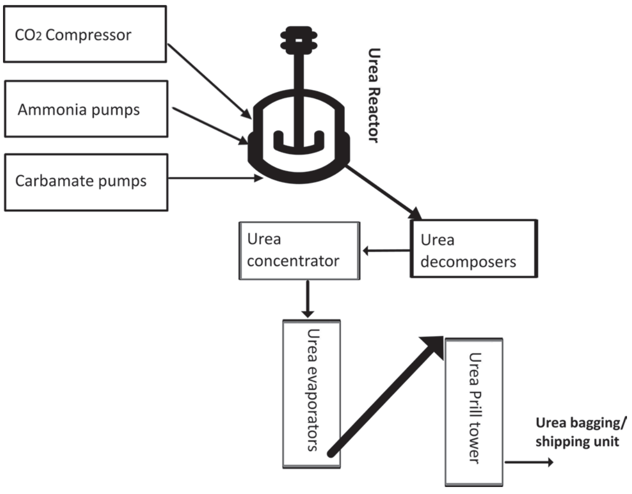

Figure 1. Urea process flow block diagram

**Corresponding Author:*
Muhammad Imran Rashid,
E-mail: muhammadimran_rashid@yahoo.com.

DOI: https://doi.org/10.30564/omms.v1i1.515

2.1 Urea Unit Compressor System

CO_2 from ammonia section stripper section flows towards urea unit and there are vacuum breakers on this line to avoid line rupture in case of compressors starvation of CO_2. Different exchangers are installed on this line in order to heat CO_2 so that it does not liquefy in a way when it's being transferred to CO_2 compressors. There are also few drains on this line to drain any condensate present or moisture if condenses during its journey to urea unit.

When CO_2 enters urea unit, it first passes through knock out drum (K.O.D.). K.O.Ds are installed to remove any water vapors (moisture) present in gaseous CO_2. CO_2 gas and water vapors have a swirling motion in a K.O.D. and when water vapors struck the drum walls, they are condensed and removed through different drains installed on K.O.D. This mechanism involved both fluid mechanics and heat-transfer operations knowledge incorporated.

CO_2 from first K.O.D. enters the compressor suction storage vessel. This vessel may also be called as a surge vessel and is horizontally laid. This vessel also helps as a CO_2 storage for a while if CO_2 shortage occurs, that's why it may be called as surge vessel. This vessel also have drains in order to drain moisture or liquid water still present after the gas passes through the first K.O.D.

If discharge pressure of compressor first stage increases, then kick back controllers installed on discharge line operates and high pressure CO_2 is pushed back to the surge tank. This phenomenon is purely fluid mechanics.

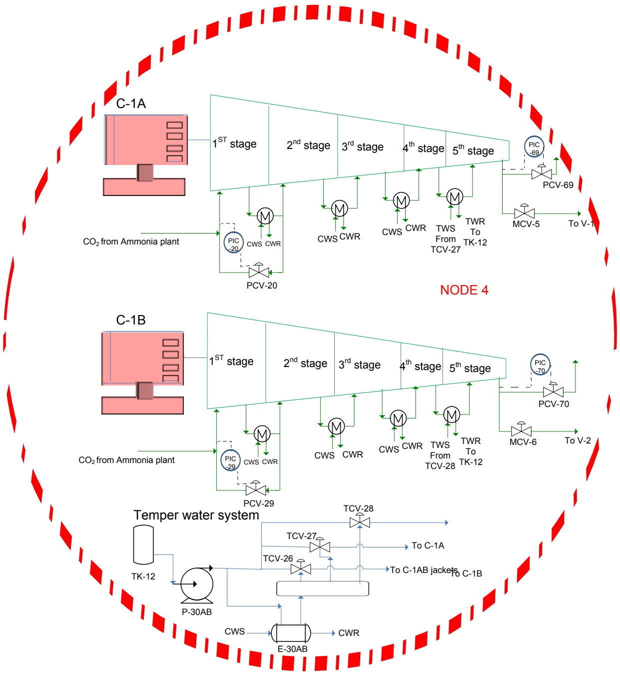

Figure 2. Urea unit compressor system diagram[5]

2.2 Compressor Stages

When CO_2 enters first stage, it is being compressed using Aluminum pistons. When CO_2 compresses, heat is generated due to compression. To dissipate this heat, compressor stages are being cooled by tempered water system whose temperature is maintained at a fixed level. After CO_2 passes through different stages, then it enters fifth stage. At suction K.O.D. of fifth stage, temperature switches are installed to avoid CO_2 freezing at low temperature as it becomes close to its critical temperature and pressure.

On each suction K.O.D. of each stage, different unloaders are installed to vent CO_2 and release excessive pressure if builds up during the compressor operation. These unloaders are kept open during the compressors start-up phase and are then slowly closed. After fifth stage discharge, CO_2 compressed enters urea reactor system.

Different inter-stage coolers are installed between different stages of the compressor. CO_2 gas is cooled in these coolers and cooling tower water acts as a cooling media for these coolers. Pressure rupture discs are installed on these coolers in case of excessive pressure. Heat-transfer operation is the leading mechanism happening here. The discussed system may be called compressor system.

2.3 Ammonia Pumps System

Ammonia from ammonia storage vessel from ammonia unit is transferred through pumps to the urea unit ammonia storage tank. This tank is horizontal (T-1, Figure 3) and also serves as a ammonia storage and may be called as a ammonia surge tank. This tank has different drains and also serves as an ammonia purifier as oil and moisture present in ammonia is drained here. From ammonia storage tank, ammonia is transferred to ammonia recovery tank (T-2), through electric and steam driven ammonia pumps.

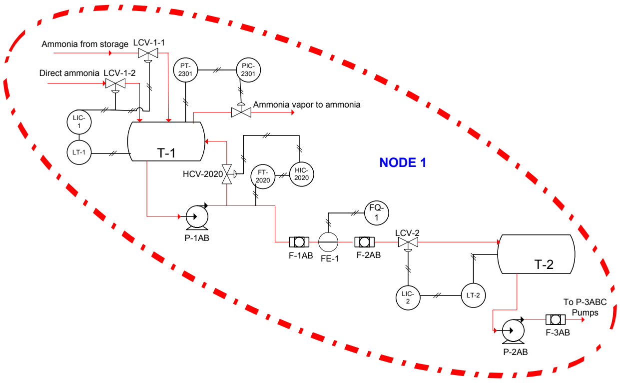

Figure 3. Ammonia storage and recovery vessels

Ammonia recovery tank is relatively bigger and also

DOI: https://doi.org/10.30564/omms.v1i1.515

serves as a suction storage and to avoid pulsations in ammonia flow to ammonia pumps. Also recovered ammonia from process which is excessive ammonia from the reactors, through condensers is recovered and transferred in this ammonia recovery tank. Ammonia recovered from process system is also relatively at higher temperature and serve to maintain temperature here as well. Ammonia from this vessel is also transferred to ammonia pumps through ammonia booster pumps.

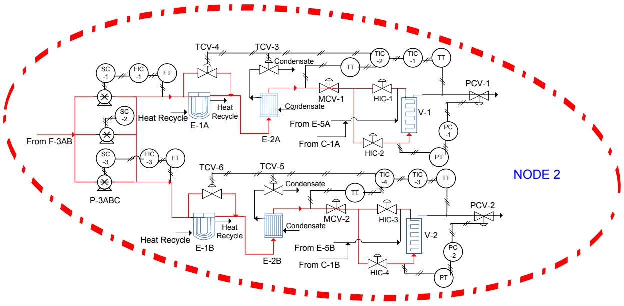

Figure 4. Urea unit ammonia pumps system diagram[5]

Ammonia pumps are positive displacement pumps with five pistons in each of the three pumps (P-3ABC, Figure 4). Ammonia pumps are primed on ammonia before their start up. Ammonia pumps pressurize ammonia and then it's fed to the urea reactors.

After CO_2 and ammonia reaction in urea reactor at 3300 psig and 383 °F, urea and ammonium carbamate formation occurs inside the reactor. Also residual ammonia and CO_2 is present which are recovered or reused in a process at later stage.

2.4 Urea Decomposition Section

Urea, ammonium carbamate, unreacted CO_2 and unreacted ammonia are transferred to the decomposers which are installed after the urea reactors. High pressure, medium pressure and low pressure decomposers are installed in a series in order to decompose ammonium carbamate present in mix form with urea and to purify urea for product formation. Urea is purified to a level of 70-80% in these decomposers and then is passed through the urea concentrator where steam and vacuum combination is used to increase urea purity to almost 90%. In this vessel combination of heat-transfer and fluid mechanics is employed.

2.5 Urea Prill Tower Section

After urea concentrator, almost 90% urea is transferred to urea evaporators, which are three in number and installed parallel. In urea evaporators, 55 psig and 185 psig steam is directly and indirectly contacted in order to increase urea purity close to 95-99%. Also dry air is fed to evaporators to dry urea. Urea from evaporators is fed to the bucket which is installed on the top section of the prill tower.

Prill tower acts like a forced draft cooling tower, as urea prills drop down from the bucket, air is sucked into tower base from around the periphery of prill tower and moves up and is released from the top of the tower carrying moisture which was present in the prills. This may be called as a free convection mechanism. Dried prills move from prill tower basement through a scrapper which is installed there towards the dried urea conveyors and is transferred towards bagging and shipping unit for packaging.

2.6 Carbamate Pumps System

Excessive ammonia and CO_2 from decomposers are fed to the carbamate recycle cooler (E-3, Figure 5), where they react to form ammonium carbamate, which is also fed to the urea reactors through carbamate pumps (P-5ABC).

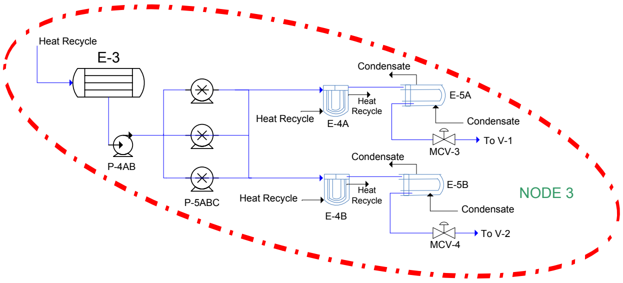

Figure 5. Urea unit carbamate pumps system diagram[5]

3. Overall Process Description of Urea Unit

Urea unit can also be divided into following sections for simplicity.

Synthesis
High pressure decomposition and absorption
Low pressure decomposition and absorption
Recovery
Vacuum concentration
Finishing and prilling

3.1 Synthesis Section

This is the section where urea synthesis takes place. In this section raw materials ammonia, carbon dioxide and recycle ammonium carbamate solution are pumped to reactors at sufficient pressure and temperature to promote the reaction.

Following two reactions occur in reactors besides some side reactions at these conditions

High pressure=3200 Psig

DOI: https://doi.org/10.30564/omms.v1i1.515

High temperature=375-383 °F
Excess ammonia=4.5/1(NH_3/CO_2)
Residence time=25-30 min
$CO_2+2NH_3=NH_4COOHNH_2$
$NH_4COOHNH_2=NH_2CONH_2+H_2O$
Overall reaction
$CO_2+2NH_3=NH_2CONH_2+H_2O$
Reactor Outlet Analysis
Ammonia=38-39%
CO_2=10-11%
Water=18-19%
Urea=32-33%

Urea synthesis section is discussed in detail at the end of the overall process description for simplicity and better understanding.

3.2 High Pressure Decomposition and High Pressure Absorption Section

High pressure decomposition takes place in liquid distributor, 1st pre-decomposer, 1st decomposer and 1st separator. Due to reduction of pressure at outlet of reactors, flashing occurs which separates 95% ammonia here and urea concentration is increased step by step. Gases from 1st separator mostly consist of CO_2 which are fed to heat recycle where it reacts with ammonia to form carbamate and exothermic reaction heat is utilized for heating purpose in decomposers and pre-heaters.

3.3 Low Pressure Decomposition and Low Pressure Absorption Section

Products solution from 1st separator flows to 2nd flash separator with letdown in pressure. Decomposition of carbamate is achieved with flashing due to drop in pressure. Gaseous phase separates from the liquid and urea conc. increases. The product solution from the 2nd Separator goes to the degasser where residual ammonia from the urea product is removed at a low pressure of 7-8 psig. The product from the degasser is transferred to the filters for the removal of any iron particles or any oil present in the product.

3.4 Vacuum Section

The product from the filters is transferred to the urea concentrator in which its temperature is increased for removal of residual gases under vacuum in concentrator separator. The gases from the concentrator goes to the hot well from where water is separated and removed gases with help of hydrolyser stripper goes to the low pressure absorption section.

3.5 Finishing and Prilling

The concentrated urea from the concentrator having a conc. of 80-90 % is sent to three evaporators for further conc. improvement. Urea enters the evaporators from the top and is distributed by the liquid distributors in the tubes. The heated air from air heaters enters the evaporator tubes. At shell side of evaporators the 55 psig steam is used for heating. Evaporators concentrate the urea to 95-99% and then urea solution from evaporators goes to head tank. From here the urea solution is fed to the buckets for prilling in the prill tower. The scrapper bellow the bucket under the base of prill tower collect the urea product and then with the help of conveyers it is send to the bagging and shipping.

4. Detailed Process Description of Urea Synthesis Section

In this section raw materials ammonia, carbon dioxide and recycle ammonium carbamate solution are pumped to reactors at sufficient pressure and temperature to promote the reaction.

Ammonia is received in T-1 (ammonia receiver, Figure 3) from ammonia unit through LCV-1-1 and LCV-1-2. Ammonia is received almost at a temperature of 15 °F which also contains 0.1—0.25% moisture to avoid the stress corrosion cracking. Ammonia is obtained from two different sources i.e. direct ammonia from ammonia production line or ammonia from storage. Ammonia is received at low temperature and pressure (almost 140 psig). From T-1 ammonia is transferred to T-2 (ammonia process vessel) with the help of pumps P-1 A/B. Ammonia flow through strainers (F-1 A/B, F-2 A/B), flow meter FQ-1 and T-2 level control valve LCV-2. T-2 also receives recovered ammonia from the process which was used in excess.

Pressure of ammonia is raised to 300 psig by booster pumps, P-2 A/B. Ammonia then through strainers F-3 A/B is fed to P-3 ABC suction (Figure 4). Pressure of ammonia is further raised to 3000-3300 psig by P-3 ABC. Three reciprocating plunger pumps operate in parallel to feed to two identical reactors V-1 and V-2. Three ammonia pumps are provided with variable speed drive which enables ammonia flow control at different load conditions. At 100% load conditions, 300gpm ammonia is required for each reactor. One pump can give maximum 200 gpm ammonia flow. So P-3A feed to reactor V-1 and P-3B feed to reactor V-2 while P-3 C is on split flow.

High pressure ammonia is passed through ammonia pre-heaters (E-1 A/B) to increase its temperature from 80 °F to 185-190 °F. A bypass line is provided on ammonia

DOI: https://doi.org/10.30564/omms.v1i1.515

line to pre-heaters (E-1 A/B) for temperature control. Process heat is recovered in these pre-heaters. Heat is recovered from heat recycle stream. Temperature of ammonia is further increased to 270 °F when ammonia passes through ammonia heaters (E-2 A/B) before entry to reactor.

Ammonia heaters (E-2A/B) are two sets of shell and tube heat exchangers with counter current flow of streams. Ammonia flows in the tubes at a pressure of 3000-3300 psig counter current to the heating condensate. Maximum temperature maintained is 270 °F which is maintained through control valve (TCV-3/TCV-4) on outlet heating source. Above 270 °F flashing of ammonia takes place which is undesirable. In ammonia heaters temperature is increased with help of process condensate.

Ammonia then at a temperature of 240-270 °F is fed to reactors via block valves, motoyama valves (MCV-1, MCV-2) and two control valves (HIC-1, HIC-2, HIC-3 & HIC-4) for each reactor for top and bottom ammonia feed lines. Motoyama valves are quick shut off valves. These valves are provided at ammonia, carbamate and carbon dioxide feed lines of both reactors. These valves close within 2 seconds of tripping of corresponding compressor or pump motor to avoid back flow of urea solution to respective lines.

Reactors top and bottom temperatures are controlled by manipulating ammonia temperatures at outlet of ammonia heaters. Bottom ammonia feed line enters the reactor after making a liquid seal against reactor's head to avoid back flow of reactors' solution to bottom line. Bottom ammonia to some extent controls the bottom temperature of reactor and mainly serves as a sensing point for reactor pressure transmitter.

CO_2 is directly received from ammonia unit in compressor's 1st stage suction knock out drum via block valve at a pressure of 0.5-4.0 psig. Three vacuum breakers are installed at suction line to save rupture of lines in case of vacuum formation. Also a pressure controller is installed at the suction line to avoid high pressure in case of compressor tripping. Pressure of CO_2 is raised to 3000-3300 psig by a five stage reciprocating compressors. 5th stage compressor has six cylinders i.e., two from first stage and one cylinder for each subsequent stage. First stage cylinder has four capacity pockets i.e. two for each cylinder one small and one large. Capacity can be varied from 59.5% to 100% by making different arrangements.

Both CO_2 compressors are interchangeable and can feed CO_2 to any reactor. But at a time only one compressor can feed to one reactor. Temperature of CO_2 after 5th stage is 245-280 °F and without any further treatment CO_2 is directly fed to reactor through a block valve and motoyama valve. CO_2 feed line is mixed with ammonia and carbamate feed line just before its entry to reactor.

Carbamate recovered in high pressure absorber cooler E-3 is fed to the suction bottles of high pressure carbamate feed pumps P-5 ABC (Figure 5). At a pressure of 280-320 psig by P-4 A/B pumps. Pressure of carbamate is raised to 3000-3300 psig by P-5 ABC. Temperature of carbamate at this stage is 185-200 °F. The high pressure carbamate is passed through carbamate pre-heaters (E-4 A/B) where its temperature is raised to 220—230 °F by heat exchange with heat recycle stream. The carbamate is in the tubes at a pressure of 3000-3300 psig while heat recycle is on the shell side at a pressure of 300 psig. There is no temperature control device installed at these pre-heaters due to low boiling point liquid phase formed in the heat recycle.

Temperature of carbamate is further raised to 260-265 °F when it passes through carbamate heaters (E-5 A/B), heating media in this case is process condensate. Temperature is manually controlled by manipulating condensate outlet and by pass valves. High temperature can cause corrosion and erosion of lines and valves.

There are two identical reactors for two lines of urea unit. The shell of reactor is a multi-ply vessel having outer layers of special grade carbon steel and inner most two layers of 316L stainless steel also named as liner. The inner liner is in direct contact with reactants. There are 28 numbers of tubes inside the reactor. The top ends of tubes are connected to reactors top main head flange through a manifold. The bottom ends of tubes are connected to a deflector head to facilitate the upward swirling flow. The tubes have 90^0 bends for better heat exchange and reaction. Tubes are supported with baffle plates. Whole assembly of baffles and tubes is supported with four angles throughout the total length of reactor.

At reactor outlet line specially designed high pressure angle block valve is installed mainly for isolation and pressure control. After angle valve two let down valves are installed in parallel at the outlet line i.e. main let down valve (PCV-1/PCV-2) and mini let down valve. Main stream of reactor outlet passes through the main let down valve and enters the bottom section of liquid distributor after let down in its pressure from 3200 psig to 320 psig. A small stream of reactor outlet goes to reflux cooler for temperature reduction. After wards it passes through the mini let down valve for pressure reduction and finally enters the top section of liquid distributor.

Reactor pressure is controlled by letdown valves at 3200 psig. Pressure transmitter of reactor is installed at bottom ammonia line to avoid blockage and corrosion of transmitter diaphragm. Reactor bottom and top temperatures are controlled by controlling the temperatures of ammonia and carbamate feed. NH_3/CO_2 mole ratio is

DOI: https://doi.org/10.30564/omms.v1i1.515

maintained by adjusting ammonia flow. Reference for correct molar ratio is drawn from the differential temperature. Reactor top temperature is its outlet temperature (380-383°F).

Temperature after let down/flashing of reactor effluent through main let down valve is a flash temperature (250-260 °F). Differential temperature is a difference of reactor top temperature and flash temperature. Its controlling range is 120—130 °F. Temperature differential is directly proportional to NH_3/CO_2 mole ratio.

Following reactions occurs in the reactor at elevated temperature (380—383 °F) and elevated pressure (3200 psig).

$$CO_2 + 2NH_3 \rightarrow NH_4COONH_2 + 155\text{Kj/g-mole (Exothermic)}$$

(Ammonium carbamate)

The second reaction of urea formation from carbamate is relatively slow and requires heat (42 Kj/g-mole).

$$NH_4COONH_2 + 42\text{ Kj/g-mole} \rightarrow NH_2CONH_2 + H_2O$$

(Urea)

Overall reaction

$$CO_2 + 2NH_3 \rightarrow NH_2CONH_2 + H_2O$$

(Urea)

Reaction is promoted by

- High pressure (3200 psig)
- High temperature (375—383 °F)
- Excess ammonia (4:1, NH_3/CO_2 mole ratio)
- Residence time (25—30 min)

Reaction is retarded by

- Excess of water
- Excess of carbamate recycling
- High temperature at insufficient pressure
- Excess retention time in reactor
- Lower temperature
- Lower pressure

Reactor feed analysis

CO_2 = 100%

NH_3= 100%

Carbamate feed approximate analysis

CO_2 = 34% max.

NH_3= 40%max.

H_2O= 20% max.

Urea= 4-8%

Reactor effluent approximate analysis

CO_2 = 10—11%

NH_3= 38—39%

H_2O= 18—19%

Urea= 32—33%

5. Conclusion

Working of urea unit is explicitly explained. This article is useful for training operators, training engineers and expert unit shift engineers as well as fresh engineer graduates (Chemical, Mechanical, Electrical, Instrument, etc.) who are seeking career in fertilizer plants.

References

[1] Rashid et al. Implementation issues of PSM in a fertilizer plant: An operation's engineer's point of view. Process Saf Prog. 2013; 32:59–65.

[2] http://www.csb.gov/west-fertilizer-explosion-and-fire-/

[3] http://www.prnewswire.com/news-releases/coffeyville-nitrogen-fertilizer-plant-adjusts-turnaround-dates-104163358.html

[4] Nigel Hyatt, "Guidelines for process hazards analysis, hazard identification and risk analysis", CRC press, 2003. ISBN 0849319099.

[5] Rashid MI and Ramzan N. Urea Synthesis Hazard Analysis—PHA, HAZOP and Quantitative Risk Assessment, 2012, LAP LAMBERT Academic Publishing AG & Co. KG, Dudweiler Landstraße 9966123 Saarbrucken, Germany, pp: 100, Standard ISBN: 978-3-659-18032-3.