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Advancing Green Urea Recovery Flow: Enhancing Efficiency Through Flow Conditioning to Control Turbulence and Pressure Drop

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Abstract

Green urea production requires high efficiency, in addition to reducing carbon emissions, high efficiency is needed to prevent waste from being wasted too much. High turbulence results in the creation of biuret that can interfere with the efficiency of urea production, one of the solutions that can be used to overcome this problem using flow conditioners. The purpose of this study is to reduce turbulence that is associated with urea production, so that it can increase efficiency in the production process. The analytical method is used to analyze and select the flow conditioner design, with the aim of having the most optimal turbulence and pressure drop values. The numerical method of Computational Fluid Dynamics (CFD) is also used in this study, the purpose of which is to validate the results and visualize the flow. The results show that the difference between the results of the analytical and numerical methods is not more than 5%, and the turbulence value can be reduced by about 5x by only losing about 0.3 bar of pressure from the system without the use of flow conditioners. This shows that the green urea production process can be more efficient and reduce the waste produced.

Keywords**:** *green urea, turbulence, pressure drop, CFD, flow conditioner.*

1. Introduction

Urea fertilizer is the most widely used nitrogen-based fertilizer in the agricultural world, more than 50% of farmers use urea as a source of nitrogen for plants [1]. The need for fertilizer has become very high in the last century, as evidenced by the increase in fertilizer use from 31 megatons (1961) to 195 megatons (2021), an increase that has occurred 6 times [2]. The increase in fertilizer demand will continue to occur, considering that food security is the goal in the 2nd SDGs, namely "Zero Hunger". The increase in urea fertilizer production will be proportional to the emissions produced. In the last two decades, the emissions generated from agricultural activities have been increasing, with the application of N fertilizer contributing about 70% of N_2O emissions from agricultural activities in rice fields [3]. The SDGs also have the goal of reducing waste in the production and consumption process as mentioned in point 12, namely "Responsible Consumption and Production". Therefore, a balance is needed between increasing fertilizer production and reducing emissions due to the production process. One of the solutions that can be used is to produce green urea using the recovery flow method.

The conventional urea production of NH_3 and CO_2 compounds is not processed optimally, this is because the production process is only carried out in one stage. The recovery flow method is carried out to increase efficiency by utilizing pressure and temperature loops, so that the rest of the production can be reprocessed. The flowrate in the process was 1,859.99 kg/h (NH_3 inbound), 9.11 kg/h (NH_3 outbound), 1,851.00 (recovered NH_3), and 3,269.15 kg/h (CO_2 inbound), 3,258 kg/h (CO2 out), 10.61 kg/h (CO_2 recovered in ionic liquid) [4]. Figure 1 shows the urea production scheme using the recovery flow method. The process begins with the incoming CO_2 being synchronized into the rectifying colum and reactor, in the mixing box CO_2 and NH_3 are mixed. The remaining residue will be flowed to the HP Scrubber, at this stage the residue will be removed and the CO_2 and NH_3 that have been mixed are increased in pressure and temperate before entering the reactor. The reactor produces urea (CON_2H_4) which is in the form of

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crystals or granules through the evaporator process. Rectifying columns play an important role in recovery, by recirculating compounds so that they can be reacted, thereby increasing the efficiency of urea production [5].

Urea production is a reaction between NH_3 and CO_2 to form dehydrated ammonium carbamate into urea. Challenges and problems in urea production are the control of side reactions such as the formation of biuret and isocyanic acid which can reduce product quality. This problem can be mitigated by setting the temperature at 170–220°C and the pressure at 125–250 bar [6]. In addition, the use of transition metal-based catalysts (Ni, Fe, Ru) can improve the efficiency of NH_3 and CO_2 synthesis. The dehydration method using N-phosphonium salts-specific reagents allows for more selective urea conversion, which shows the importance of the combination of catalysts and dehydration methods in improving energy efficiency and selectivity in urea production using CO_2 [7]. Biomass gasification technology is also the optimal solution for green urea production in the period 2020-2035 with a lower cost than conventional methods, PV electrolysis method is predicted to be a solution in the future due to the decrease in the price of electrolysis technology with a progress ratio of 82% [5]. The $Fe/MgAl_2O_4$-based chemical looping method shows stable performance in the conversion of NH3 and CO_2 into syngas, a two-reactor approach system that allows more efficient separation of N_2 can reduce the gas purification process after the reaction occurs [8]. Multi-Stage Solvent Circulation (MSC) technology was also developed to reduce emissions in urea production. The combination of NH_3 and K_2CO_3 as an absorbent to capture CO_2 and SO_2, the CO_2 capture efficiency reaches 84.1%-95.4% depending on the incoming CO_2 rate. The MSC method aims to reduce energy consumption by 25% compared to the conventional method [9]. In addition to the main factors in urea production such as temperature and pressure, turbulence and pressure drop also play an important role in reaction efficiency [5]. Too high turbulence can increase the mixing between CO_2 and NH_3 gases, which can increase reaction conversion in reversible systems. However, excessive turbulence can also lead to the formation of by-compounds such as biuretes that degrade the quality of urea. On the other hand, excessive pressure drops can reduce reaction efficiency by increasing the energy requirements in the system, while too small a pressure drop can increase unwanted turbulence[12]. Therefore, an optimal balance between turbulence and pressure drop is necessary to improve urea production efficiency. Turbulence of the flow into the reactor can also affect the efficiency of the reaction in the production of green urea, one way to control the turbulence of CO_2 and NH_3 is by using a flow conditioner.

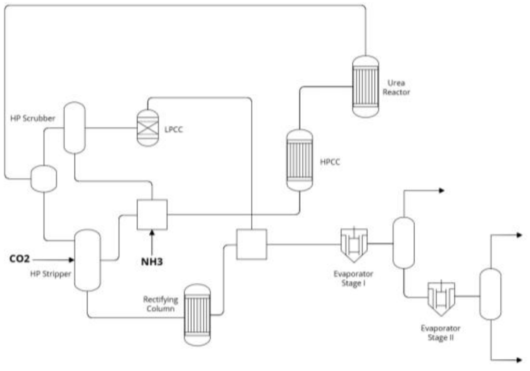


Figure 1. Green Urea Recovery Flow Production

Flow conditioners can reduce turbulence that occurs due to excessive temperature or pressure. Optimizing the design of flow conditioners is important to do, this is because if the pressure and turbulence are drastically reduced, the reaction between CO_2 and NH_3 is inefficient [11]. Turbulent fluctuations can increase reactant mixing and can result in higher conversions in reversible systems such as urea reactions [10]. Turbulence also increases the mass in CO_2-based production such as in urea reactions, to analyze such numerical methods such as Computational Fluid Dynamics (CFD) can be used [11]. However, too high a turbulence value that occurs in a urea reaction will cause side reactions such as the formation of biuret which can reduce efficiency in production [6]. Therefore, the right combination of turbulence and pressure drop that occurs in the manufacture of urea is needed. This optimization can be done using an analytical approach [10]. Reviewing this, the optimization of Flow Conditioning using an analytical approach, and computational fluid dynamics can be carried out. The purpose of this study is to find a design with an optimal combination of turbulence and pressure drop, so that it can improve the efficiency of the reaction in the manufacture of green urea.

2. Method

2.1 Boundary Condition

The production of urea involves NH_3 and CO_2, the operating conditions in urea production are 170–220°C and the pressure is 125–250 bar, but in this simulation the temperature is around 170°C and the pressure is 130 bar. High pressure and temperature make the turbulence value of the instantaneous large, which leads to the formation of biuret which reduces production efficiency [6]. The pipe that is commonly used in the ammonia industry is 2-4 in, in this study the pipe with the largest diameter was chosen to reduce the turbulence that occurs and the safety of the pipe when subjected to high pressure. The length of the flow conditioner used is 0.5 m, while the diameter is below 4 in, i.e. 1/4 in, 1/2 in, 3/4 in, 1 in, 1 1/4 in, 1 1/2 in, and so on up to 4 in. The flowrates of NH_3 and CO_2 were 1,859.99 kg/h and 3,269.15 kg/h, respectively [4]. The design of the flow conditioner must be able to reduce turbulence but must also pay attention to the pressure drop that occurs. Figure 2 shows the design of the Flow Conditioner which is somewhat used in urea production.

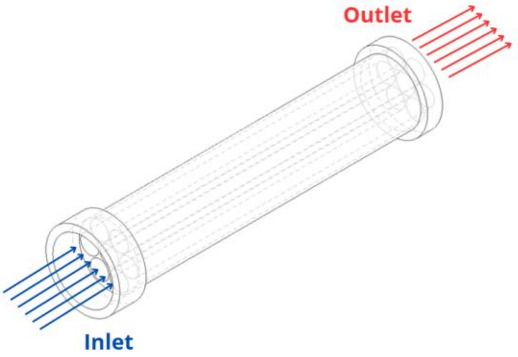


Figure 2. Desain Flow Conditioner

2.2 Analytic Method

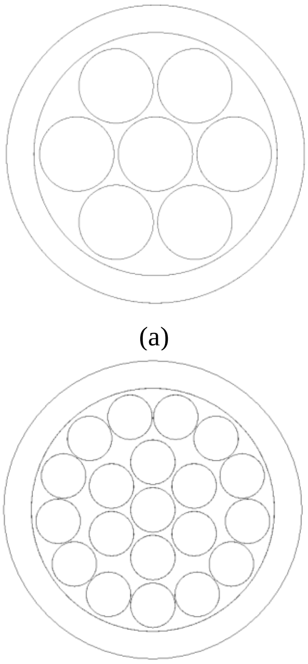
Determining the design of the flow conditioner can be calculated by the continuity equation shown in equation 1 [12]. Where A_1 is the inlet cross-sectional area, which is 4 in and V_1 is the initial inlet speed obtained from the flowrate of each fluid. A_2 is the cross-sectional area of the diameter to be selected in the flow conditioner so that it can find out how much speed (V_2) occurs in the diameter of the outlet. Keep in mind that after finding the diameter used, it must be multiplied by the number of existing pipes as seen in Figure 3, this is because the smaller the diameter used, the larger the pipe that can be accommodated and will affect the cross-sectional area of the flow conditioner.

$$V_2 = \frac{A_1 \times V_1}{\text{Quantity of Pipe Outlet} \times A_2} \qquad (1)$$

After the velocity of the outlet is known, the turbulence value can be calculated using the Reynolds number indicated by equation 2 [13]. The density of each fluid is indicated by ρ , while the dynamic viscosity is indicated by μ. D is the diameter of the outlet pipe used to reduce turbulence that occurs in the flow.

$$Re = \frac{\rho V D}{\mu} \qquad (2)$$

The number of Reynolds that has been known will be a consideration in choosing the optimal design in making flow conditioners.



(a)

(b)

Figure 3. Design Flow Conditioner (a) 1½ in (b) ¾ in

Calculating the pressure drop that occurs due to changes in the speed and diameter of the pipe, the pressure drop (ΔP) can be calculated through equation 3 [14]. Where f is the friction coefficient of the fluid and material used, the length of the flow conditioner is shown by L. The density uses the fluid used (ρ), for the velocity (V) using the calculated result using equation 1 and the diameter using the outlet diameter on the flow conditioner (D). Figure 3 shows how the design details on the flow conditioner.

$$\Delta P = f\frac{L}{D}\frac{\rho V^2}{2} \tag{3}$$

$$\text{Total } \Delta P = \text{Total Pipe} \times \Delta P \tag{4}$$

So that it can be known the total pressure drop that occurs in the flow conditioner design by multiplying the number of pipes in the design by the pressure drop value (ΔP). An example can be seen in Figure 3 that if using a diameter of 1½ in, the calculated pressure drop (ΔP) value is multiplied by 7 by the number of pipes in the flow conditioner.

2.3 Numerical Method

Computational Fluid Dynamics (CFD) is one of the most effective numerical methods in analyzing fluid dynamics, so it can be a validation of an analytical approach. There are two equations that can be used in analyzing turbulence that occur in a flow, namely the Navier-Stokes equation shown by equation 5 and the Ginxbrug-Landau model shown in equation 6.

$$\rho\frac{Dv}{Dt} = -\nabla P + \mu\nabla^2 v + F \tag{5}$$

$$\rho_0\frac{D\phi}{Dt} = \nabla\cdot(L\nabla\phi) - NF'(\phi) + \alpha G'(\phi)v_s^2 \tag{6}$$

ρ is the density of the fluid, P describes the pressure, μ for viscosity, and F is the external force. Equation 6 shows the relationship between the order parameters and the fluid flow dynamics used to describe the transition between the flow of the hydrant or turbulent [15].

The equation connecting pressure drop, vicous dissipation and the turbulence energy spectrum is shown in equation 7 [16].

$$\Delta P = -\frac{1}{VA}\int_{\Omega}\tau:\nabla u \, d \tag{7}$$

τ shows the viscose stress, ∇u is the velocity gradient, and V represents the volume of the fluid One of the methods that can analyze turbulence and pressure drop that occurs in pipes is CFD [14]. This shows that a numerical method can be used to find a combination of diameter, turbulence, and pressure drop in green urea flow conditioner.

3. Result and Discussion

The analytical method produces Reynolds numbers and pressure drops experienced at each pipe diameter used in the flow conditioner design, Table 1 and 2 shows the resulting analytical calculations. The data of the Reynolds number was obtained from the results of the calculation of equations 1 and 2, while the pressure drop value was obtained from the calculation of equations 3 and 4. Figure 4 shows how the turbulent value compares to the pressure drop that occurs.

Table 1. Results of Analytical Methods NH_3

Diameter (in)	**NH_3**	
	Reynolds	**Pressure Drop (Pa)**
¼	65,608.91	363,500.86
½	86,931.81	30,102.41
¾	115,909.08	7,928.21
1	248,376.60	5,375.43
1 ¼	198,701.28	1,761.42
1 ½	289,772.70	1,238.78
1 ¾	331,168.79	764.19
2	434,659.04	587.94
2 ¼	772,727.19	652.53
2 ½	695,454.47	385.31
2 ¾	632,231.34	239.25
3	579,545.39	154.85
3 ¼	534,964.98	103.78

3 ½	496,753.19	71.64
3 ¾	463,636.31	50.74
4	434,659.04	36.75

Table 2. Results of Analytical Methods CO_2

Diameter (in)	CO_2	
	Reynolds	Reynolds
¼	86,111.70	86,111.70
½	114,098.00	114,098.00
¾	152,130.67	152,130.67
1	325,994.28	325,994.28
1 ¼	260,795.43	260,795.43
1 ½	380,326.66	380,326.66
1 ¾	434,659.04	434,659.04
2	570,489.99	570,489.99
2 ¼	1,014,204.43	1,014,204.43
2 ½	912,783.99	912,783.99
2 ¾	829,803.63	829,803.63
3	760,653.33	760,653.33
3 ¼	702,141.53	702,141.53
3 ½	651,988.57	651,988.57
3 ¾	608,522.66	608,522.66
4	570,489.99	570,489.99

The optimal point of the two fluids is at 1/2 in diameter where the point between the Reynolds and the pressure drop meets, as shown in Figure 4 which shows that there is no significant reduction in the pressure drop but a very large increase in the Reynolds number after ½ in diameter. The smaller the diameter, the smaller the number of Reynolds produced, which is also shown in equation 2 where the number of Reynolds is directly proportional to the addition of diameter [13]. The increase in the diameter of the pipe affects the flow transition so that it has an impact on the flow characteristics and pressure distribution in the pipe, which causes the number of Reynolds to increase [17]. The decrease in the pressure drop value is directly proportional to the increase in diameter, which is shown in equation 3. This is due to a decrease in flow velocity and a lower friction factor, so that it can minimize the pressure drop that occurs in the pipeline [18].

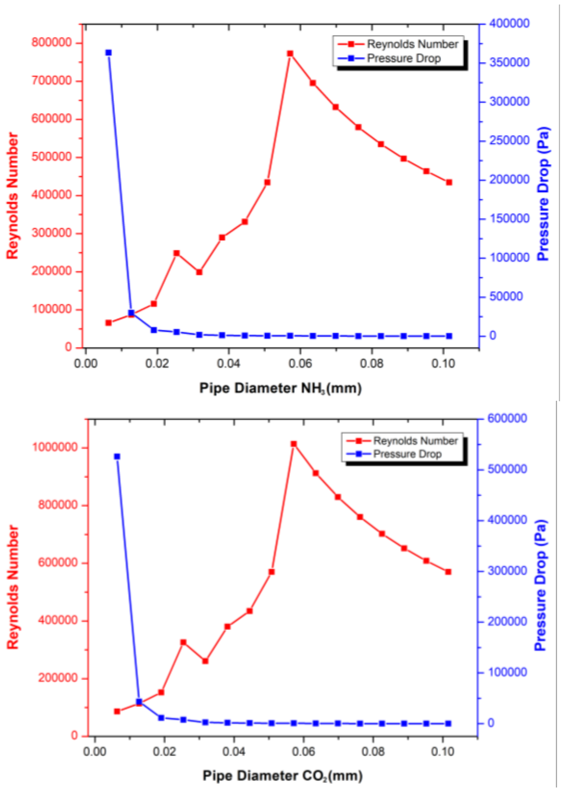


Figure 4. Comparison Graph of Reynolds Number with Pressure Drop on NH_3 and CO_2 Pipe Diameter

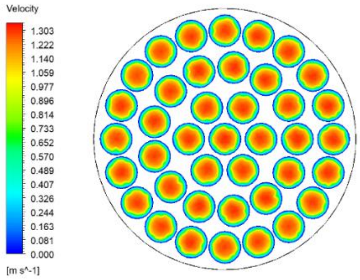
Table 2 shows how the sensitivity of diameter changes in the variables, where showing the smallest diameter change will certainly be greater in pressure loss. This can happen because the smaller the diameter of the pipe, the more pipes are used in the flow conditioner. The event causes the fluid to come into more and more contact with the pipe walls, thus causing a large loss of pressure. The smaller the Reynolds number, the faster the flow velocity occurs, which causes a high turbulence value. However, the influence of surface area also has an effect as seen in the various sensitivity values, because there is a difference in the number of pipes used in each diameter to be selected. At the optimum diameter of 1/2 in, it can be seen that the turbulent value has decreased considerably, namely with a sensitivity of 80% and experienced a pressure loss with a sensitivity of 8%.

Table 2. Sensitivity of Diameter Changes to Velocity, Reynolds, and Pressure Drop using One at a Time (OAT)

Diameter (mm)	Velocity (m/s)	Reynolds Number	Pressure Drop

			(Pa)
0.00635	71%	85%	98.912%
0.0127	60%	80%	8.182%
0.01905	42%	73%	2.148%
0.0254	78%	43%	1.453%
0.03175	46%	54%	0.469%
0.0381	78%	33%	0.327%
0.04445	74%	24%	0.198%
0.0508	100%	0%	0.150%
0.05715	46%	78%	0.168%
0.0635	64%	60%	0.095%
0.06985	90%	45%	0.055%
0.0762	78%	33%	0.032%
0.08255	51%	23%	0.018%
0.0889	31%	14%	0.009%
0.09525	14%	7%	0.004%
0.1016	0%	0%	0.000%

However, the number of Reynolds can be reduced even though there is an increase in diameter, this is because the diameter of 1 in and 1 ¼ in has the same number of pipes, which is as many as 7 pieces but with different pipe diameters. This event causes a difference in velocity that occurs in each pipe, where the faster the flow, the higher the number of Reynolds produced [19]. Because it will affect the friction factor that occurs and the pressure distribution that occurs. The cross-sectional area of a 1 ¼ in diameter pipe is larger than that of 1 in, with the same number of pipes but different diameters affecting the resulting cross-sectional area in a flow conditioner[12]. This will affect the velocity of each diameter causing the Reynolds number to fall, other events shown at diameters of 2 ¼ in and above.



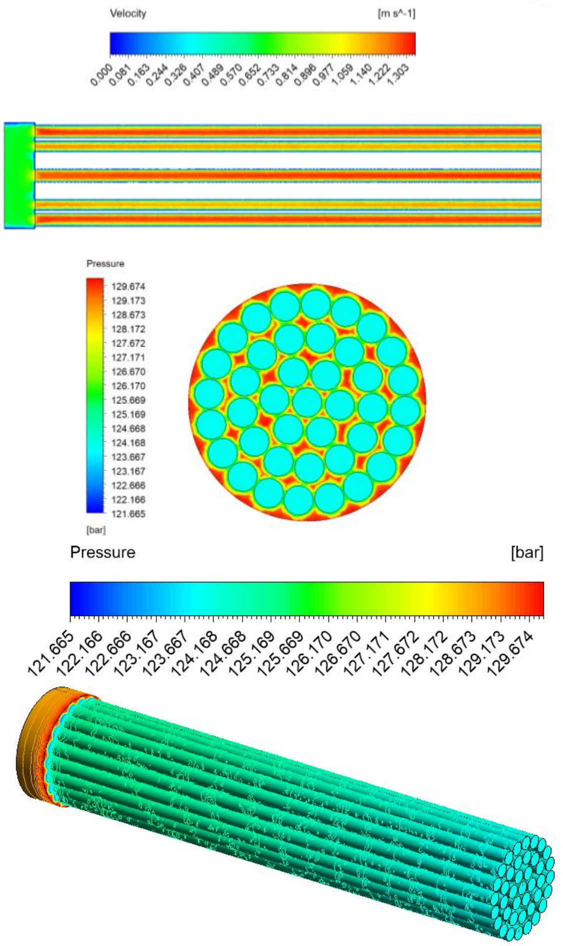
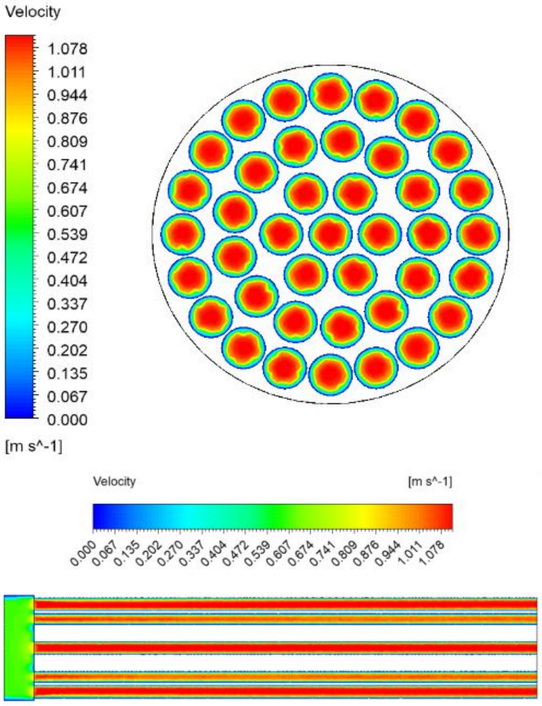


Figure 5. Simulation Velocity and Pressure Drop NH_3



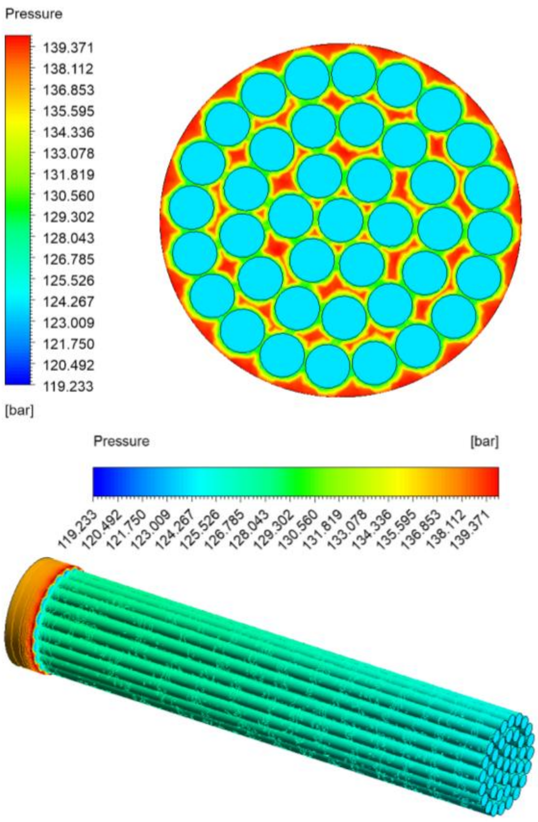


Figure 6. Simulation Velocity and Pressure Drop CO_2

The results of the simulation using the numerical method can be seen in figures 5 and 6, the results show that there is no significant difference between the results of the analysis using the analytical and numerical methods (CFD). The Reynolds number and NH3 pressure drop values in the numerical method are around 84.674.29 (V = 1,099 m/s) and 31.332 Pa, while in CO_2 the Reynolds number is around 110,458.25 and the pressure drop is 42,168 Pa. This shows that the difference in results or errors in the two methods is less than 5%, so the results of the two methods can be accounted for. Errors 5% is considered a reasonable compromise between precision and practicality in the field [22]. This difference is due to the numerical calculation using external force viscose stress in doing the calculation [16]. This decrease in turbulence value will certainly increase the production efficiency of green urea, where the turbulence effect is reduced by more than 5x but only loses pressure by about 0.3 bar. It should be noted that in the synthesis of urea the efficient Reynolds number is about 106, an overly laminar flow will also slow down the chemical reaction process. Therefore, a flow conditioner is needed so that turbulence in chemical reactions can be controlled [6].

It should also be noted that there is a difference in Reynolds number values and pressure drops that occur in both fluids, because there are differences in density and viscosity values in both fluids. Where CO_2 has a higher value compared to NH_3, thus affecting the Reynolds number value and the pressure drop that occurs [14]. The high density will affect the inertial force that occurs, which causes the fluid to remain moving in its flow pattern which causes turbulence to be difficult to control. The greater the density and viscosity values of the fluid, the greater the inertial force and the friction that occurs also causes the fluid to lose more pressure [16].

In its application in the industrial world with 4 in pipes, there is a significant sequence of Reynolds number values, with conventional methods without using flow conditioners, the Reynolds number experienced by NH_3 and CO_2 is around 400,000 and 500,000 [4]. However, by using a flow conditioner the turbulence can be reduced by about 320,000-400,000 with only a pressure loss of about 0.3-0.4 bar. This shows the high performance of the flow conditioner in reducing the turbulence that occurs. Also keep in mind that the design of the flow conditioner must adjust to the size of the pipe that will be used in the production of green urea.

4. Conclusions

This research aims to increase efficiency in green urea production by optimizing turbulent and pressure drop values using flow conditioners. The results showed that the optimal dimension where the turbulence value and pressure drop were balanced, namely the flow conditioner design with a diameter of 1/2 in, the design consisted of 40 pipes with a length of 0.5 m. The analytical method shows that Reynolds' number at NH_3 is 86,931.81, while the pressure drop value is around 30,102.41 Pa.

In CO_2, the Reynolds number produced was 114.098 and the pressure drop value was 43.580.09 Pa. To validate the results, it was carried out by numerical methods, namely computational fluid dynamics. The method produces Reynolds number values and pressure drop of around 84,674.29 and 31,332 Pa, while CO_2 produces Reynolds numbers of 110,458.25 and pressure drop of about 43,580.09 Pa. The difference in the results of the two methods is not more than 5%, so the results of the analysis can be accounted for. The turbulent value conditioning is 5x lower but only loses about 0.3 bar of pressure from pipes that do not use flow conditioners, so the production efficiency of green urea can also be increased. It is necessary to redesign the flow conditioner according to the temperature, speed, and dimensions of the pipes used. Therefore, boundary conditions greatly affect the design of flow conditioners that will be used in the production of green urea.

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