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Research Article

Reducing Energy Consumption in the Formaldehyde Production Process

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Abstract

Formaldehyde is a substance that has been utilized for a long time due to its numerous benefits. This research article focuses on optimizing energy consumption in formaldehyde production from methanol using metal oxide catalysts. The Formox process is one of the main methods for formaldehyde production through the partial oxidation of methanol with metal oxide catalysts. In this process, energy released by the system is recovered and reused, making the overall energy consumption more efficient and reducing the required costs. By reducing the energy consumed in the production process, emissions released into the atmosphere will decrease, and profitability can be enhanced by lowering energy-related costs. The energy results before modification show a value of 43,030,653.8 kJ/h, while the modified system yields 26,766,429.7 kJ/h, achieving an energy efficiency improvement of 37.8%.

Keywords: Formaldehyde; Formox; Metal Oxide; Process Modification; Energy Efficiency

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1. Introduction

Formaldehyde, with the chemical formula CH_2O, is the simplest and most abundant carbonyl in the atmosphere [1]. The production of formaldehyde typically involves the conversion of methanol into hydrocarbons, which can yield promising materials for converting gas and coal into fuels and chemicals, [2]. This compound has a wide range of uses and industrial applications, particularly due to its role as one of the key compounds in the chemical manufacturing industry. Formaldehyde is also a key component in the synthesis of industrial resins such as melamine-formaldehyde, urea-formaldehyde, and phenol-formaldehyde. Its derivatives, widely used in wood and furniture processing, carpets and textiles, as well as construction, make formaldehyde an important material in the global economy [3]. Formaldehyde also has other benefits, including its use for disinfecting, as a preservative, and for killing bacteria. Since the 19th century, formaldehyde has played an important role in preserving biological tissues. However, formaldehyde contains harmful properties as it is corrosive to metals, toxic if ingested, hazardous upon skin contact, and can cause cancer, making it dangerous to both humans and the environment [4]. Despite these risks, formaldehyde is still widely used due to its diverse benefits, especially in various industries. There are three common processes used in the industrial production of formaldehyde: the silver process, the BASF process, and the Formox process [5].

About 30% of the methanol produced is used to synthesize formaldehyde, which is utilized in various branches of the chemical industry [6]. Formaldehyde is industrially produced from methanol using various methods such as the silver method, BASF, and Formox. The main differences

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between these production methods are the type of catalyst, operating conditions, and feed concentration. Methanol oxidation with a silver-based catalyst at temperatures of 600–700 °C is the oldest process for producing formaldehyde, marketed by BASF. In this process, the reaction temperature and conversion depend on the methanol concentration in the feed stream. In the Formox process, marketed by Johnson Matthey Process Technologies, methanol and oxygen react at temperatures of 300–400 °C in the presence of an iron oxide catalyst. Due to the higher stability of the iron oxide catalyst compared to the silver catalyst and the lower operating temperature, the Formox method has attracted more attention than the silver method. Modifications can be made to reduce the energy consumption [7].

This paper aims to bridge the gap by providing a comprehensive analysis of optimizing energy consumption in the formaldehyde production process using the Formox method, through the reuse of heat generated from the final product in a heat exchanger. By reducing the energy consumed in the production process, the emissions released into the atmosphere will decrease, and profitability can be enhanced by lowering energy-related costs.

2. Material and Methods

2.1 Methods

In the production of formaldehyde, methanol and metal oxide catalysts are used. The formaldehyde production process consists of three main stages: steam reforming of natural gas to produce synthesis gas, which is then converted into methanol through the methanol synthesis reaction (carbon monoxide hydrogenation), and finally, the partial oxidation of methanol to produce formaldehyde. Formaldehyde is primarily produced industrially through two main reactions: one is the dehydrogenation of methanol, and the other is the partial oxidation of methanol. The reactions are as follows [3]:

$$CH_3OH \leftrightarrow CH_2O + H_2 \quad \Delta\hat{H}_r^\circ = +84\ \text{kJ/mol} \qquad (1)$$

$$CH_3OH + \frac{1}{2}O_2 \rightarrow CH_2O + H_2O \ \Delta\hat{H}_r^\circ = -159\ \text{kJ/mol} \qquad (2)$$

Reaction (2) is exothermic. The thermal energy released in this reaction maintains the reactor temperature while simultaneously facilitating the shift of equilibrium towards the right in reaction (1). This enhances formaldehyde formation [8]. The three commonly used processes in formaldehyde production are the silver process, the BASF process, and the Formox process.

The silver method (Figure 1) is a conventional formaldehyde production process based on the oxidative dehydrogenation of methanol. The synthesis process is implemented as a water-weighted process to ensure the long lifespan of the silver catalyst used [9]. This method requires high temperatures, typically between 600-650 °C, to achieve a methanol conversion rate of 85%. The high temperature requirement leads to high operating costs. Additionally, the silver method requires catalyst regeneration every 3-8 months. However, this method has a lower initial investment cost due to the smaller size of the plant [10].

The BASF method (Figure 2), which has been widely used since 1927, is favored not only for its economical production costs but also for its extensive process references [11]. The BASF method is a methanol synthesis process that develops catalytic hydrogenation with metal catalysts at high pressure. Carbon monoxide hydrogenation, which produces methanol with metal catalysts, is carried out at a temperature of

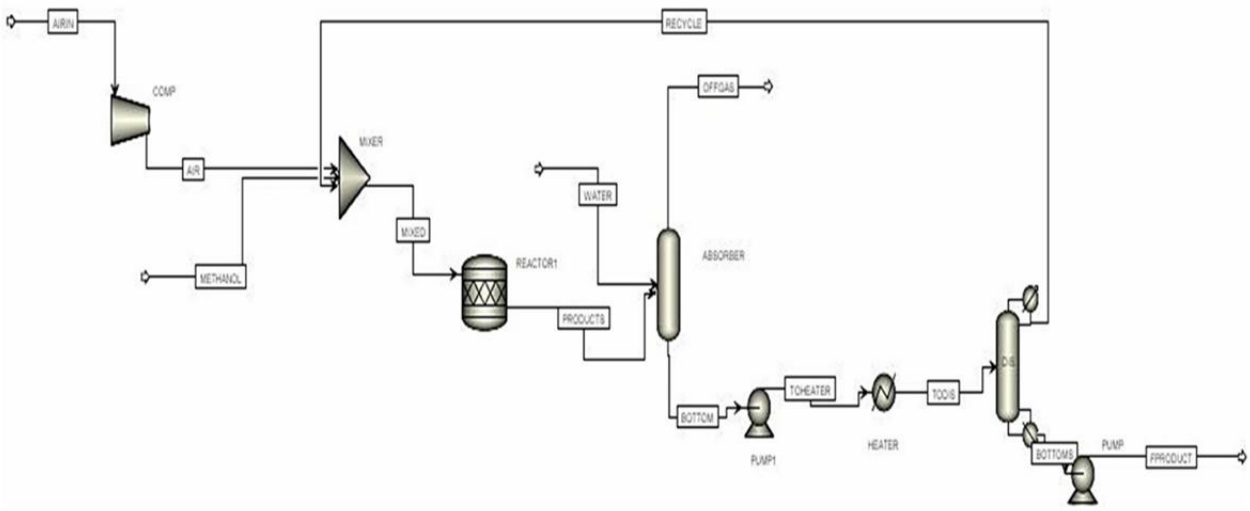

Figure 1. Silver method process [10]

500 °C and high pressure (100 bar). Both the silver method and BASF use a fixed bed of silver catalyst operating at atmospheric pressure with a large excess of methanol. However, because BASF operates at a higher temperature, the methanol conversion obtained is higher than that of the silver method [12]. However, this method results in low methanol yields due to the pollutants present in the reactant gases [13].

The catalyst commonly used in formaldehyde production from methanol using the Formox method (Figure 3) is metal oxide semiconductor (MOS), which has been considered a promising candidate due to its low cost, ease of operation, excellent sensitivity, rapid response and recovery, as well as high physical and chemical stability [14]. The Formox process is one of the main methods for formaldehyde production through the partial oxidation of methanol with metal oxide catalysts. In this process, methanol is vaporized and mixed with air and recycled gas from the absorption system. It is then reacted in a multitubular packed bed reactor. The resulting products consist of nitrogen, water, formaldehyde, oxygen, methanol, carbon monoxide, and dimethyl ether [15]. The Formox process operates under pressures around 250–400 °C, with excess air, and a MeOH conversion rate of over 99%, yielding between 88-92% [16].

Essentially, all three processes use silver catalysts. However, the Formox process is considered the best. This is because the Formox process uses silver catalysts in the form of metal oxide, which is designed to be more durable and efficient in maintaining its catalytic activity. The catalyst used is a nanometer-sized catalyst that provides greater efficiency and conversion. The fine particle size of the catalyst creates a larger surface area, offering more active sites that can interact with the reactants. With the ease of interaction at these active sites, the catalyst operates more efficiently [17].

2.2 Efficiency Energy in Formox Method

Optimizing chemical processes at their optimal points can significantly reduce costs, energy consumption, and risks within the system. Numerous studies in the literature have focused on this optimization, particularly in chemical

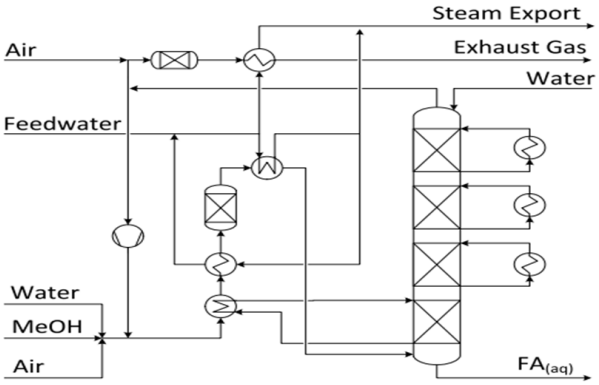

Figure 2. BASF method process [11]

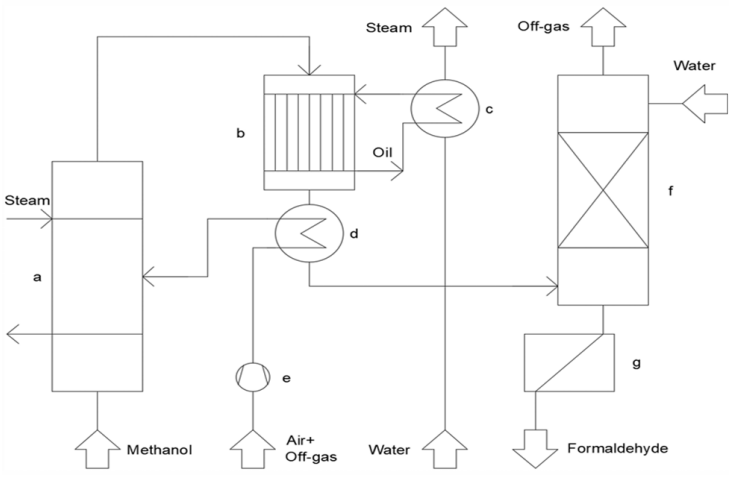

Figure 3. Formox method process [14]

reactors, highlighting the benefits of improved efficiency, enhanced product quality, and increased safety [18]. Improving the energy efficiency of industrial processes and the facilities in which they are carried out is often considered to be one of the most promising ways to begin reducing global greenhouse gas emissions. One of the best ways for organizations to reduce their energy consumption without having to carry out extensive equipment and energy recycling [19]. Energy efficiency is optimized to produce the desired product with minimal energy consumption.

In this paper, energy efficiency is carried out in formaldehyde production using the Formox method. Efficiency is done by utilizing the reactor product as a hot fluid to heat the feed, distillation condeser energy as a heater source and the energy released by the reactor is utilized as a source of reboiler energy in distillation. This energy utilization can reduce the energy used during production thus reducing production costs.

In the formaldehyde formation process, a pre-treatment step involving heating is applied to the feed entering the reactor. This heating is performed to increase the yield of the process. The feed then reacts in the reactor. Due to the exothermic nature of the reaction in the reactor, the product is a hot mixture of formaldehyde. This mixture must continuously be cooled to prevent damage to its components, as shown in Figure 4. In Figure 4, it can be observed that several pieces of equipment are required for this process, including pumps, heaters, and coolers during the pre-treatment stage. This process consumes a significant amount of energy, making it a candidate for modification to improve efficiency. The proposed modification is shown in Figure 5. The temperature of the product produced in the reactor can be used as a heat fluid in a heat exchanger for pre-treating methanol. By utilizing the reactor's product, it can heat the methanol to a high temperature, thereby increasing the yield in the reactor. Additionally, this process indirectly helps cool the formaldehyde mixture, minimizing potential damage to other components.

In addition to methanol, air also undergoes a pre-treatment process. This process is shown in Figure 6, the air is first heated using heater E-

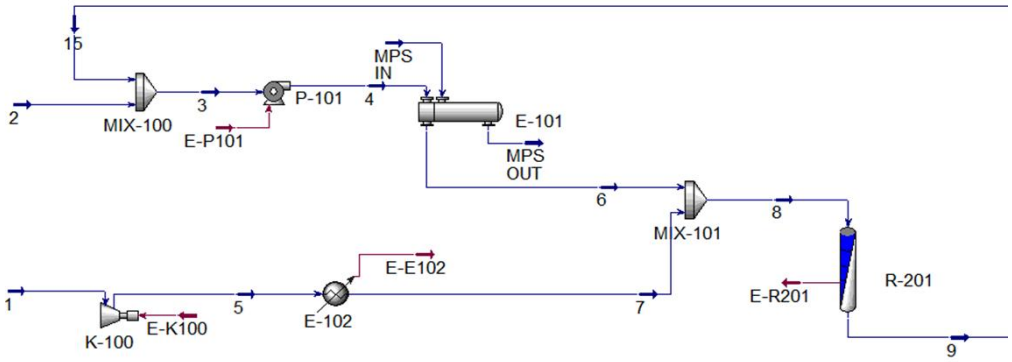

Figure 4. HYSYS simulation of unmodified of methanol heating process

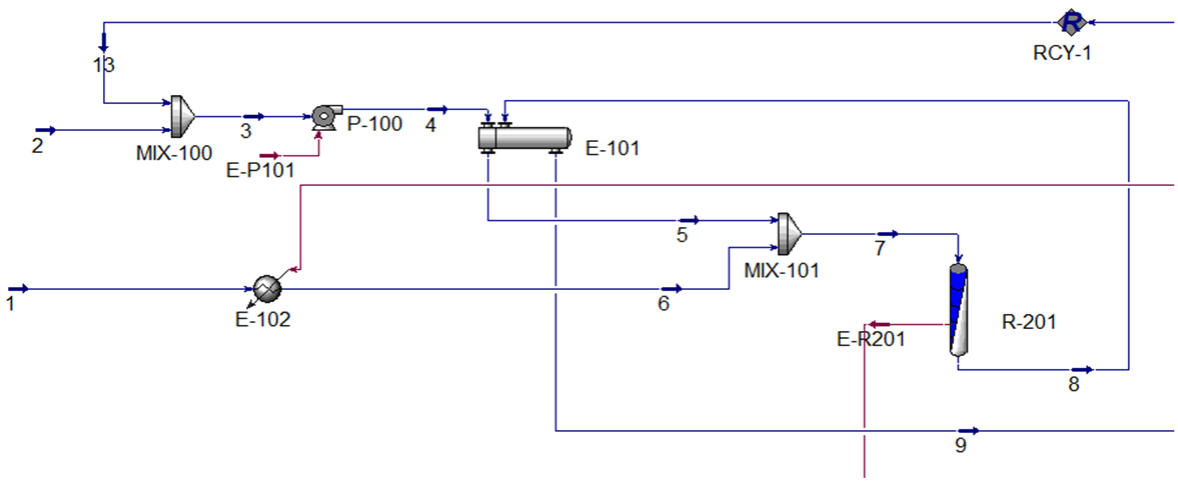

Figure 5. HYSYS simulation of modified of methanol heating process

102, and then it is mixed with methanol using MIX-101. The resulting mixture is then fed into the reactor, where it generates energy. The energy produced is significant and has the potential to be used for other utilities. The condenser in T-102 also generates substantial energy, which can be harnessed. The utilization of energy from the reactor (R-201) and the condenser (T-102) is illustrated in Figure 7. The energy generated by the reactor can be used as a source of energy for the reboiler in T-102. Since the energy requirements are similar, the energy from the reactor can be utilized by T-102 to assist in the distillation process. Additionally, the energy from the condenser in T-102 can be used as a source of energy for E-102. By utilizing the energy from the condenser, the feed can be reheated, ensuring that the mixture entering the reactor reaches its optimal temperature range of 300-400 °C. This improves the conversion rate, leading to higher efficiency and a greater yield.

After the simulation, the energy used in the unmodified process and modified process will be calculated. These energy results will be compared and the energy efficiency will be calculated. Energy efficiency can be calculated using the following equation:

$$\text{Efficiency} = \frac{\Delta H_{\text{unmodified}} - \Delta H_{\text{modified}}}{\Delta H_{\text{unmodified}}} \times 100\% \quad (3)$$

Where, Efficiency is efficiency percentage (%), $\Delta H_{\text{unmodified}}$ is total energy of unmoldified process (kJ/h), $\Delta H_{\text{modified}}$ is total energy of modified process (kJ/h).

2.3 The Thermodynamic and Kinetic Aspects of Formaldehyde Formation

From the formaldehyde process, the data for the standard enthalpy of formation ($\Delta H°_f$) at a temperature of 298 K is obtained from the book by Coulson [20]. The calculation of enthalpy of reaction at temperatur 298 K:

$\Delta H_{\text{reaction}} = (\Delta H_{f,\text{product}} - \Delta H_{f,\text{reactan}})_{298}$
$\Delta H_{\text{reaction}} = -201.3 - (-357.97)$
$\Delta H_{\text{reaction}} = -156.671$ kJ/kmol

Based on the calculations, it can be concluded that the formaldehyde formation reaction is exothermic due to the negative $\Delta H°_f$ value. From this process, the Gibbs free energy value is also obtained as follows:

Gibbs energy ($\Delta G°_{298K}$):
$\Delta G°_{298K} = \sum \Delta G_f°\text{product} - \sum \Delta G_f°\text{reactant}$

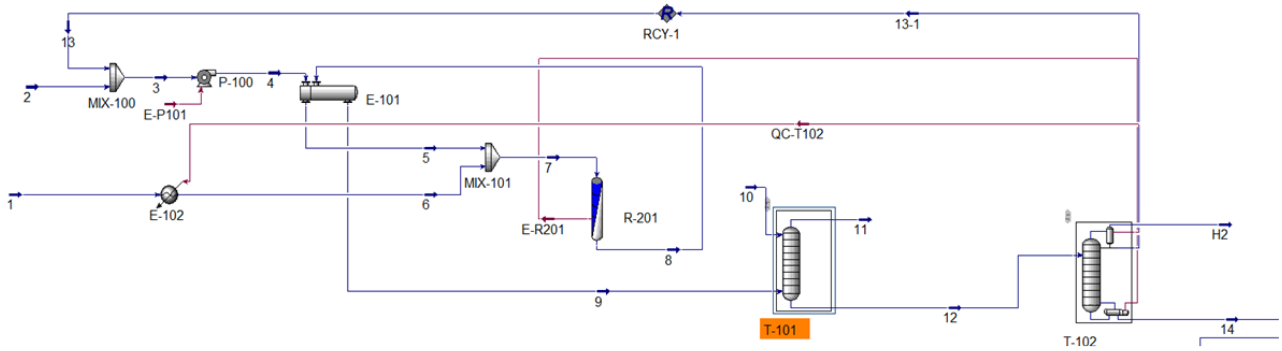

Figure 6. Unmodified of air heating process and reactor energy utilization

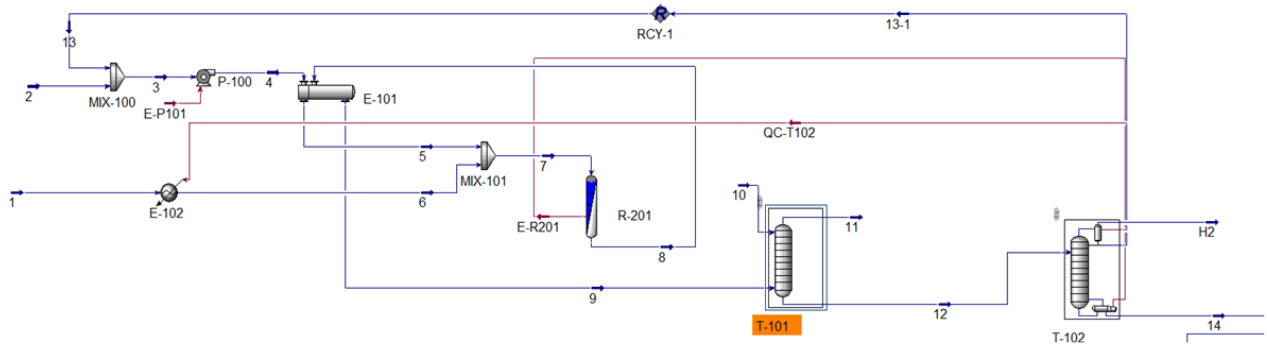

Figure 7. Modified of air heating process and reactor energy utilization

$$= (\Delta G_f°CH_2OH + \Delta G_f°O_2) - (\Delta G_f°CH_2O - \Delta G_f°H_2O)$$
$$= (-162.51 + 0) - \left(91.2 + (-228.6)\right)$$
$$= -25.11 \text{ kJ/mol}$$

Equilibrium constant (K_2) in the standard state:

$$\Delta G°_{298K} = -RT \ln K$$
$$\ln K_2 = -\frac{\Delta G°_{298K}}{RT} = \frac{25110 \frac{J}{mol}}{8.314 \frac{J}{mol} \times 298 \text{ K}}$$
$$= 10.135$$
$$K_2 = 2.5 \times 10^4$$

Equilibrium constant (K_1) at reactor temperature T = 300 °C:

$$\ln \frac{K_1}{K_2} = \frac{-\Delta H_R}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

$\Delta H°_{298K}$ = Standard heat of reaction at 298 K.

$$\ln \frac{K_1}{2.5 \times 10^4} = \frac{156671 \frac{J}{mol}}{8.314 \frac{J}{mol}.K}\left(\frac{1}{573 \text{ K}} - \frac{1}{298 \text{ K}}\right)$$
$$\ln \frac{K_1}{2.5 \times 10^4} = -30.35$$
$$K_1 = 1.65 \times 10^{-9}$$

Based on the calculation, the equilibrium constant value of the reaction operates at 300 °C (K_{573}) = 1.65×10^{-9}, so the reaction is reversible.

3. Results and Discussion

3.1 Simulation of Chemical Process and Modified Chemical Process

Aspen HYSYS is a software used to simulate the formaldehyde formation process. This software has features that can simulate a process. Then we can see specifically the effect of each tool on the process. This feature makes the process of optimization and analysis of the system far more flexible and through. Here are several limitations associated with HYSYS that need to be addressed. The software lacks certain processes and conditions essential for the production of formaldehyde, necessitating the adoption of some creative approaches to achieve the desired optimization within this study's The simulation results can be seen in Figures 8-11.

The basic process of formaldehyde formation is shown in Figures 8 and 10. The target of this process is to produce 37% formaldehyde. As seen in Figure 8, both air and methanol undergo a pre-treatment process by heating. The mixture is then combined and fed into the reactor (R-201). The product from the reactor is directed into the absorber (T-101), where the purpose is to absorb the hydrogen gas generated from the reactor. The absorber used is water at a temperature of 30 °C and a pressure of 138 kPa. The output from the absorption process is then sent to the distillation column (T-102), with the goal of separating methanol from formaldehyde. The bottom product from T-102 is mixed with water and cooled using

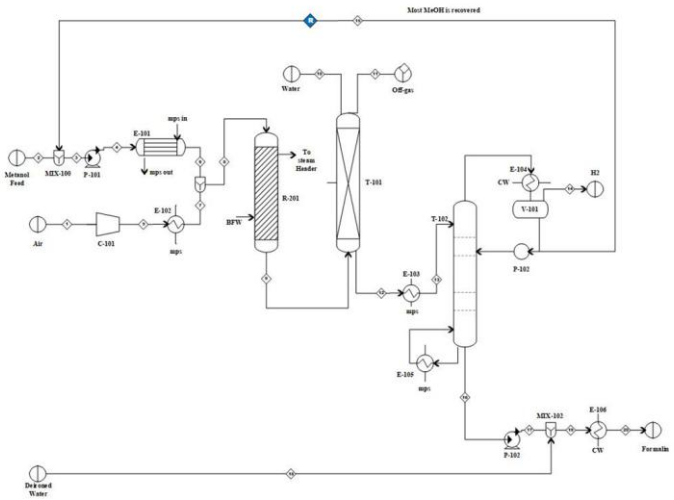

Figure 8. Process Flow Diagram of basic/unmodified process

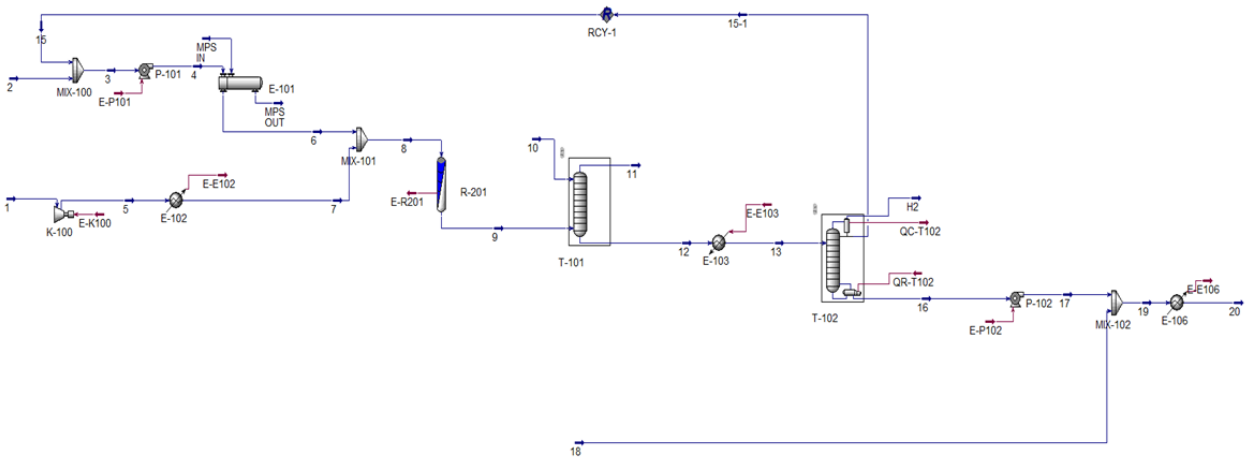

Figure 9. Unmodified process simulation using Aspen HYSYS

cooler (E-106) until the temperature reaches 30 °C.

The air heating process requires a significant amount of energy. Additionally, energy is released from the reactor, making energy efficiency crucial. Therefore, energy efficiency measures are implemented, as shown in Figures 9 and 11. In these figures, it can be seen that the energy output from the reactor is used to heat methanol. The reactor product has a temperature of 400 °C, which can be utilized to heat methanol from 25 °C to 300 °C. This is advantageous, as previously, the temperature could only be raised to 150 °C before utilization. Furthermore, Figures 9 and 11 illustrate how the energy released from the reactor is harnessed. This energy is used as a source for the reboiler in the distillation column (T-102). The energy produced by the condenser in

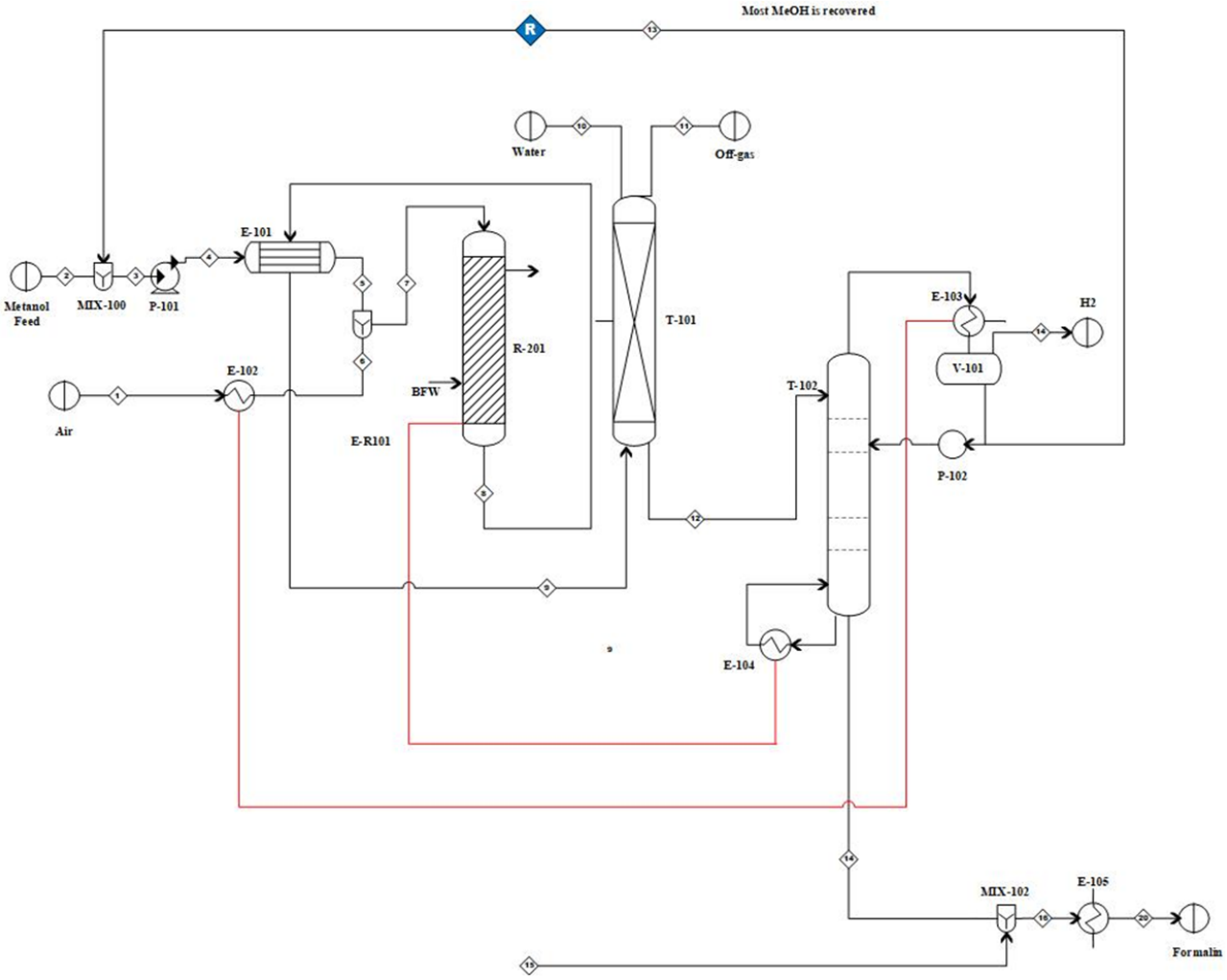

Figure 10. Process Flow Diagram of modified process

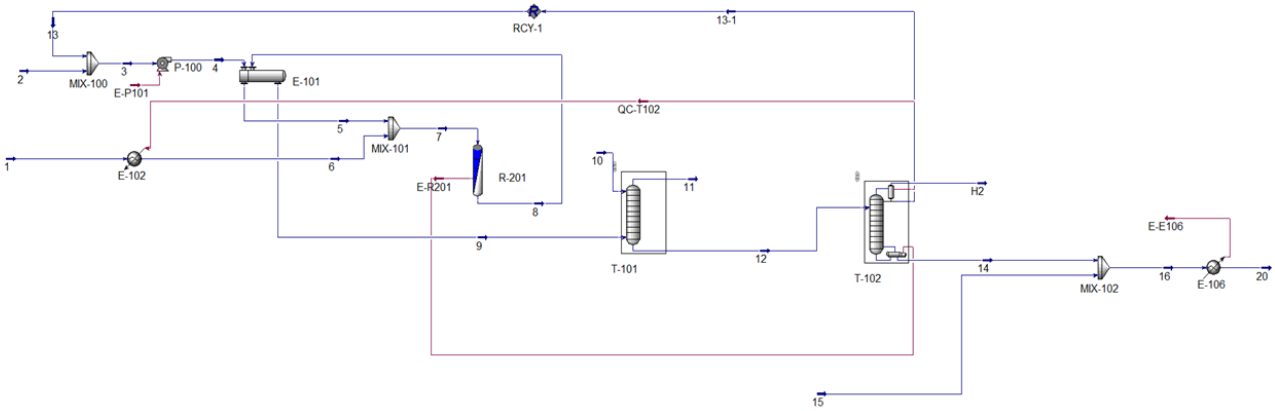

Figure 11. HYSYS simulation of modified process

the distillation column (T-102) is then utilized as a source of energy for the heater (E-102).

This modification not only impacts the amount of energy involved in the process but also leads to an increase in conversion efficiency. Before the modification, the reactor (R-201) had a conversion rate of 89.33%. However, after the modification, the reactor (R-201) achieved a conversion rate of 91.98%. This improvement is advantageous both in terms of the conversion rate and the efficient use of energy.

3.2 Efficiency Energy in Process modified

From the simulations conducted, data on the total energy required by the system was obtained. The energy is derived from the heat flow (kJ/h) of the system. This method was used to determine the energy efficiency by comparing the amount of energy required in the system before modification with that of the modified system. The heat flow for both systems is presented in Table 1.

Based on Table 2, the total energy used in the unmodified process is 43,030,653.8 kJ/h. Then, the total energy used in the modified process is 26,766,429.7 kJ/h. These results prove that the modifications that have been made have succeeded in reducing the energy used but still get the desired conversion. The amount of energy efficiency can be calculated through Equation (1). Based on this equation, the modifications made can reduce energy by 37.8%.

4. Conclusion

Based on the data obtained from the observations conducted, before the modification, the system required 43,030,653.8 kJ/h of energy. However, after the modification, the system's energy requirement decreased to 26,766,429.7 kJ/h, resulting in an energy reduction of 37.8%. To improve energy efficiency, the energy released from the reactor is used to heat methanol from 25 °C to 300 °C. This energy is also utilized to power the reboiler in T-102 and the heater (E-102). This modification not only reduces energy consumption but also improves conversion efficiency. Before the modification, the reactor (R-201) had a conversion rate of 89.33%, which increased to 91.98% after the modification. This improvement brings benefits in both conversion efficiency and more effective energy utilization. Through the research presented in this paper, it is clear that reusing the energy released from the reactor offers significant advantages to the system. We hope this can serve as a foundation for further studies on how to better integrate such systems into industrial applications.

Table 1. $\Delta H°_f$ data at 298 K temperature

Components	$\Delta H°_f$ (kJ/kmol)
CH_3OH	−201.3
H_2O	−242
O_2	0
N_2	0
CO	−110.62
HCHO	−115.97

References

[1] Dovrou, E., Bates, K.H., Moch, J.M., Mickley, L.J., Jacob, D.J., & Keutsch, F.N. (2022). Catalytic role of formaldehyde in particulate matter formation. *Proceedings of the National Academy of Sciences*, 119 (6), e2113265119. DOI: 10.1073/pnas.2113265119

[2] Liu, Y., Kirchberger, F.M., Müller, S., Eder, M., Tonigold, M., Sanchez-Sanchez, M., & Lercher, J.A. (2019). Critical role of formaldehyde during methanol conversion to hydrocarbons. *Nature communications*, 10(1), 1462. DOI: 10.1038/s41467-019-09449-7

[3] Bahmanpour, A.M., Hoadley, A., & Tanksale, A. (2014). Critical review and exergy analysis of formaldehyde production processes. *Reviews in Chemical Engineering*, 30 (6), 583-604. DOI: 10.1515/revce-2014-0022

[4] Ferreira, J.R., Rezende, L.C., Barbosa, A.D.S., De Carvalho, P., De Lima, N.E., & Carvalho, A.A. (2017). Economic, human and environmental health benefits of replacing formaldehyde in the preservation of corpses. *Ecotoxicology and Environmental Safety*, 145, 490-495. DOI: 10.1016/j.ecoenv.2017.07.072

[5] Thrane, J., Mentzel, U.V., Thorhauge, M., Høj, M., & Jensen, A.D. (2021). A review and experimental revisit of alternative catalysts for selective oxidation of methanol to formaldehyde. *Catalysts*, 11(11), 1329. DOI: 10.3390/catal11111329

Table 2. The energy analysis of unmodified and modified processes

Unmodified Process		Modified Process
Heat Flow (kJ/h)	Object	Heat Flow (kJ/h)
1,168.016	E-P101	1,114.756
780,128.2	E-R201	10,325,035
104,304.7	QC-T102	1,514,906
951,942,700	E-E106	14,925,374
171,958,200		
789,811,100		
103,674,900		
9,773.373		
126,303,990		
43,030,653.8	Total	26,766,429.7

[6] Chowdhury, A.G., Arnold, U., Garbev, K., Bender, M., & Sauer, J. (2024). Direct dehydrogenation of methanol to formaldehyde over ZnO–SiO2-based catalysts. *Catalysis Science & Technology*, 14(17), 4958-4967. DOI: 10.1039/D4CY00541D

[7] Trincado, M., Grützmacher, H., & Prechtl, M.H. (2018). CO2-based hydrogen storage–Hydrogen generation from formaldehyde/water. *Physical Sciences Reviews*, 3(5), 20170013. DOI: 10.1515/psr-2017-0013

[8] Mursics, J., Urbancl, D., & Goricanec, D. (2020). Process of formaldehyde and volatile organic compounds' removal from waste gases. *Applied Sciences*, 10 (14), 4702. DOI: 10.3390/app10144702

[9] Münzer, P., Arnold, U., & Sauer, J. (2024). Process Design for the Directly Coupled Production of Methanol and Formaldehyde Based on CO2. *Chemie Ingenieur Technik*. DOI: 10.1002/cite.202300183

[10] Shakeel, K., Javaid, M., Muazzam, Y., Naqvi, S.R., Taqvi, S.A.A., Uddin, F., Mehran, M.T., Sikander, U., & Niazi, M.B. (2020). Performance comparison of industrially produces formaldehyde using two different catalysts. *Processses,* 8 (5), 571. DOI: 10.3390/pr8050571

[11] Deng, J., Pan, T., Xu, Q., Chen, M. Y., Zhang, Y., Guo, Q. X., & Fu, Y. (2014). Linked strategy for the production of fuels via formose reaction. *Scientific Reports*, 3 (1), 1244. DOI: 10.1038/srep01244

[12] Tavares Lima, M., Salifou, N.O., Brigagão, G.V., Itabaiana Jr, I., & Wojcieszak, R. (2023). Conversion of CO2 into Glycolic Acid: A Review of Main Steps and Future Challenges. *Catalysts*, 14(1), 4. DOI: 10.3390/catal14010004

[13] Dalena, F., Senatore, A., Basile, M., Knani, S., Basile, A., & Iulianelli, A. (2018). Advances in methanol production and utilization, with particular emphasis toward hydrogen generation via membrane reactor technology. *Membranes*, 8 (4), 98. DOI: 10.3390/membranes8040098

[14] Han, Z., Qi, Y., Yang, Z., Han, H., Jiang, Y., Du, W., ... & Wang, F. (2020). Recent advances and perspectives on constructing metal oxide semiconductor gas sensing materials for efficient formaldehyde detection. *Journal of Materials Chemistry C*, 8 (38), 13169-13188. DOI: 10.1039/D0TC03750H

[15] Braz, C.G., Lutters, N., Rocha, J., Alvim, R., Kenig, E.Y., & Matos, H.A. (2020). Modeling and simulation of an industrial formaldehyde absorption system. *Industrial & Engineering Chemistry Research*, 59 (13), 5996-6006. DOI: 10.1021/acs.iecr.9b07013

[16] Lindner, B.J. (2019). Evaluation of polyoxymethylene dimethyl ether synthesis based on dual fluidized bed steam gasification. *Doctoral Dissertation*, Technische Universität Wien.

[17] Sun, S., Li, H., & Xu, Z.J. (2018). Impact of surface area in evaluation of catalyst activity. *Joule*, 2(6), 1024-1027. DOI: 10.1016/j.joule.2018.05.003

[18] Ghahraloud, H., & Farsi, M. (2017). Modeling and optimization of methanol oxidation over metal oxide catalyst in an industrial fixed bed reactor. *Journal of the Taiwan Institute of Chemical Engineers*, 81, 95-103. DOI: 10.1016/j.jtice.2017.10.003

[19] O'Rielly, K., & Jeswiet, J. (2015). Improving industrial energy efficiency through the implementation of waste heat recovery systems. *Transactions of the Canadian Society for Mechanical Engineering*, 39(1), 125-136. DOI: 10.1139/tcsme-2015-0010

[20] Lighfoot, E.N., & Sinnott, R.K. (1994). Coulson and Richardson's Chemical Engineering Vol. 6: Chemical Engineering Design. *Chemical Engineering Science-Paper Edition*, 49(12), 2032.