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Research Article

Improving Energy Efficiency with Heat Exchanger and Optimizing Operating Conditions for Sorbitol Production from Dextrose

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Abstract

Sorbitol is a sugar alcohol which has a molecular formula of $C_6H_{14}O_6$. The production of sorbitol by the hydrogenation process is carried out at high pressure so that a large amount of energy is required. The use of considerable energy in the production process supports the need for innovation for energy efficiency in the production of sorbitol from dextrose, which is expected to help increase sorbitol production so that it can meet market needs. The innovation carried out here is to change the operating conditions with the help of Ru/ASMA@AC catalyst so that the temperature required during the reaction is low. In addition, modifying the use of heat exchanger units so that the heat generated during operation is reused. These innovations were simulated using Aspen HYSYS software. The results of the simulation proved to be able to improve energy efficiency by reducing the performance of compressors and coolers used during production and saving considerable energy.

Keywords: sorbitol; dextrose; glucose; heat exchanger; energy efficiency

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1. Introduction

Sorbitol is a sugar alcohol which has a molecular formula of $C_6H_{14}O_6$. As a sweetener, sorbitol has been found useful in sugar-free and reduced-sugar products because it has the relative sweetness of 60% compared to sucrose with only 2.6 calories per gram [1]. Sorbitol in the food industry as a sweetener, but also as an important intermediate for the synthesis of vitamin C and is widely used in daily chemical industry, pharmaceutical, papermaking, coating and alternative energy, and other fields [2]. Apart from being a sweetener sorbitol is also considered for the production of dietary foods for diabetic patients as it is not dependent on the insulin metabolic pathway [3]. Indonesia occupies the second largest producer of sorbitol and starch sweeteners after China, and the Asia Pacific becomes the main area for sorbitol distribution [1]. It can be expected that the demand for sorbitol will grow more extensively so that the production of sorbitol will hold great potential in food and chemical industries that develop rapidly [4].

In general, sorbitol can be produced chemically or biotechnologically, but the chemical process via catalytic hydrogenation of glucose is the process that has been globally applied on an industrial scale. The direct production of sorbitol from cellulose using Cu/Al/Fe catalyst in a low phosphoric acid concentration (0.08%, w/w), yielding a maximum yield of 68.07% sorbitol [5].

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The simultaneous catalytic conversion of cellulose into sorbitol under H_2 pressure (50 bar) at 170 ◦C and 205 ◦C using Ru as a catalyst and pointed out a maximum yield of 75% sorbitol [6]. About 80% of sorbitol production is performed in batch mode and catalyzed by Raney nickel [1]. The chemical process of sorbitol production generally involves the catalytic hydrogenation of glucose or a mixture of glucose and fructose.

Glucose can be obtained from cheap renewable biomass sources such as starch, cellulose, and straw through hydrolysis [7]. Dextrose is a simple form of sugar obtained from biomass through starch hydrolysis. The production of sorbitol from dextrose is through a chemical process with catalytic hydrogenation. The reaction mechanism is the reduction of saccharide carbonyl groups with the reaction [8] at Scheme 1. The reaction takes place under hydrogen pressure using metal catalysts (Ni, Pt, Ru). Ni-based catalysts can be considered as the key to an efficient and economical method to hydrogenate glucose to sorbitol due to the high electronegativity of Ni.

Figure 1 depicts the basic flow chart of the sorbitol production process from dextrose [9], where there are several process stages of raw material preparation, mixing, hydrogenation, and sorbitol purification. The raw materials used are dextrose, water, and hydrogen. Dextrose is stored in a closed place to avoid contact with water because it has hygroscopic properties. Hydrogen is flowed directly from the hydrogen plant because the hydrogenation reaction that occurs requires hydrogen in large quantities so that if hydrogen is accommodated in the tank, it requires a large tank size and a lot of instrumentation equipment due to the explosive nature of hydrogen. Dextrose is mixed with water to achieve a concentration of 40% dextrose. In the hydrogenation process the hydrogen required must be high pressure so that the hydrogen feed must be increased in pressure before entering the reactor. However, it is important to note that the right H_2 pressure results in high dextrose conversion [10].

All reactants are reacted in the reactor with a temperature that is not too high so that the catalyst does not experience cracking around 100-180 °C and a pressure of 10-150 bar [11]. In addition to catalyst loading, high reaction temperatures can trigger glucose carbonization which results in increased by-products. The product exits the reactor there are still by-products and residual hydrogen so that it needs to be purified. Purification is carried out through a separation unit and the separation results are concentrated to reduce the water content [12].

Many previous studies on sorbitol production have discussed increasing production or mass efficiency. However, research on energy efficiency in sorbitol production is still limited. The efficiency process is in the form of energy saving which aims to maximize economic potential and minimize environmental impact. In sorbitol production, the hydrogenation process is a unit that needs large energy. As a result of this gap, this research aims to improve energy efficiency by utilizing heat exchangers from heat in the production unit and optimizing operating conditions. The simulation process of sorbitol production from dextrose uses Aspen HYSYS software. Aspen HYSYS allows users to describe the process quickly and effectively because the thermodynamics and operating units provided are quite accurate and comprehensive [13].

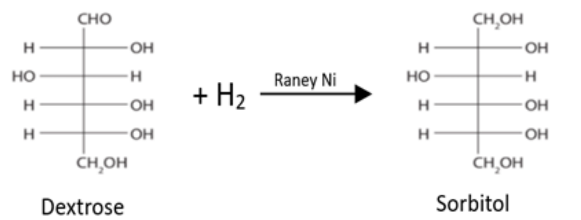
2. Method

2.1 Property Package

Aspen HYSYS has completed with various thermodynamic equations. The selection of appropriate equations is aimed at analyzing phase equilibrium and the enthalpy of mixed compounds. In this simulation process of catalytic hydrogenation for sorbitol production, the NRTL property package was used.

2.2 Optimisation of Operating Conditions

The hydrogenation process requires high-pressure hydrogen before reacting inside the



Scheme 1. Reduction reaction of carbonyl groups of saccharide.

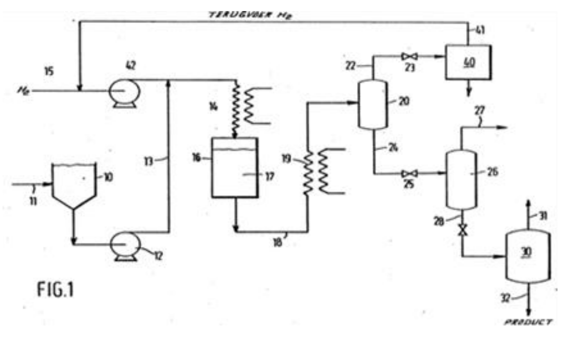


Figure 1. Basic process flow diagram of sorbitol production [9].

reactor, necessitating the use of a compressor. The compressor has specific limits on the pressure it can achieve. It is crucial to adhere to these limits to avoid damaging the compressor or the connected system. If the desired pressure is very high, multiple stages of compressors are often used. In sorbitol production, significant power is needed to compress H_2, so it is necessary to consider the optimal reaction pressure [14]. Literatures review is needed to obtain optimization of H_2 compression and simulate it on Aspen HYSYS for energy efficiency in sorbitol production through catalytic hydrogenation reactions.

2.3 Energy Optimization using Heat Exchange

Heat transfer can be carried out using a heat exchanger unit, cooler, and heater. Coolers and heaters are units that function to absorb or provide energy to fluids using energy from electricity or other sources. Meanwhile, a heat exchanger is a heat transfer unit that utilizes the heat exchange between one fluid and another without direct contact. In the sorbitol production process, heat transfer units such as coolers and heaters are used. Heat exchangers recover and reuse waste heat, there by reducing energy consumption. In the chemical industry, heat exchangers efficiently utilize the temperature difference in fluid flow to enhance energy efficiency [15].

The unit used to increase the pressure in sorbitol production is a multistage compressor so that several coolers are needed to cool before entering the next compressor. With the increase in pressure, the temperature also rises. Therefore, a cooler is needed to cool down to maintain the performance of the compressor. To increase the energy efficiency of the sorbitol production, a heat exchanger was chosen. Where this heat exchanger utilizes the available heat from during the production process. This is feasible because there is a cooling and heating process during the process so that the two flows can transfer heat without the need for additional energy from outside. Specific Energy Consumption (SEC) [18] can be calculated using the following equation:

$$SEC\ (\frac{kJ}{ton}) = \frac{Energy\ consumption\ (\frac{kJ}{tahun})}{production\ quantity\ (\frac{ton}{tahun})} \quad (1)$$

3. Results and Discussion

3.1 Simulation of Basic Process Flow Diagram

The production of sorbitol with Aspen HYSYS starts from the incoming feed until sorbitol with 70% concentration is obtained. The reaction takes place in a reactor at 130 °C and 88 bar pressure with Ni catalyst.

$$C_6H_{12}O_6 + H_2 \xrightarrow{Ni} C_6H_{14}O \quad (2)$$

Standard heat of reaction can be calculated according to standard heat of formation at 298 K at Table 1:

$\Delta H^o_{r,298K} = \Sigma\Delta H^o_{f,product} - \Sigma\Delta H^o_{f,reactant} = -58.5$ kJ/mole

From the calculation of the heat of reaction, a negative ΔH value indicates that the reaction is exothermic. Calculation of $\Delta G^o_{r,298K}$ and equilibrium constant (K) as follow (Table 2):

$$\Delta G^o_{r,298K} = \Sigma\Delta G^o_{f,298K,product} - \Sigma\Delta G^o_{f,298K,reactant}$$
$$= \Delta G^o_{f,298K} C_6H_{14}O_6 - (\Delta G^o_{f,298K} C_6H_{12}O_6 + \Delta G^o_{f,298K}\ H_2) = -169.1 \text{ kJ/mole}$$
$$\Delta G^o_{r,298K} = -R\ T\ ln\ K_{298}$$
$$ln\ K_{298} = \frac{-\Delta G^o_{r,298K}}{R\ T}$$
$$= \frac{-(-169100\frac{J}{mole})}{8.314\frac{J}{mole\ K}298K} = 68.25$$
$$K_{298} = exp^{(68.25)} = 438\ x\ 10^{29}$$
$$ln\ \frac{K_{298}}{K} = \frac{\Delta H°_R}{R}\left(\frac{1}{298} - \frac{1}{T}\right)$$
$$= \frac{58500\frac{J}{mole\ K}}{8.314\frac{J}{mole\ K}}\left(\frac{1}{298} - \frac{1}{418K}\right) = 6.15196$$
$$K = \frac{4.38\ X\ 10^{29}}{exp^{(6.15196)}} = 9.326\ X 10^{27}$$

The reaction process is carried out continuously, using a fixed bed reactor with a trickle bed system containing Raney Nickel catalyst. The reactor operating conditions are a temperature of 130 °C and a pressure of 88 atm. The selection of these operating conditions is intended to prevent the Ni catalyst from undergoing cracking. Figure 2 depicts the process flow diagram for basic process of sorbitol production, while Figure 3 shows the HYSYS simulation of the basic process. The mixture of

Table 1. Standard heat of formation at 298 K ($\Delta H^o_{f,298K}$).

Component	$\Delta H^o_{f,298K}$(kJ/mol)
Glucose	-1295.2
Hydrogen	0
Sorbitol	-1353.7

Table 2. Standard Gibbs free energy of formation at 298 K ($\Delta G^o_{f,298K}$).

Component	$\Delta G^o_{f,298K}$ (kJ/mol)
Glucose	-678.04
Hydrogen	0
Sorbitol	-866.14

dextrose and water is pumped to increase its pressure. Similarly, hydrogen is conveyed along with its recycle flow using three compressors and three coolers. Hydrogen and dextrose solution are mixed and their temperature is raised to reach the operating conditions entering the reactor, which are at a pressure of 88 bar and a temperature of 130 °C. Subsequently, the reactor output is first cooled before entering the separation unit. The bottom product of the mixture, in liquid form, enters the second separation unit, which purifies it under operating conditions of 1 bar to obtain a sorbitol solution. Then, to reduce the water content, a final separation is carried out to obtain 70% sorbitol. The top product V-100 is fed into a splitter to separate water and hydrogen. Hydrogen is purged, and pure hydrogen is circulated as a recycle.

3.2 Energy Efficiency and Operational Condition Optimization

Production of sorbitol using the same raw material at a pressure of 40 bar, but with Ru/ASMA@AC catalyst, achieves higher conversion [16]. The required pressure is lower than the previous conditions when using Ru catalyst. This directly impacts the energy used, with the compressor requiring 88 bars less (Ni catalyst) and 40 bars less (Ru catalyst). Consequently, the compression energy for H2 can be more efficient. The reduction in the desired pressure can lower compression costs, either in terms of electric energy or the reduction of equipment used [17].

As the process was modified and simulated in Figures 4 and 5, energy efficiency is achieved using a heat exchanger by harnessing the flow of streams with high temperature differences. Optimizing the performance of the heat exchanger reduces energy waste and enhances operational efficiency. Hydrogen exiting the first compressor (K-100) is cooled with a cooler before entering the second compressor. This cooling process can be replaced by a heat exchanger utilizing the flow of low-temperature dextrose solution. The dextrose solution, which absorbs the heat, can reduce the workload of the heater before entering the reactor.

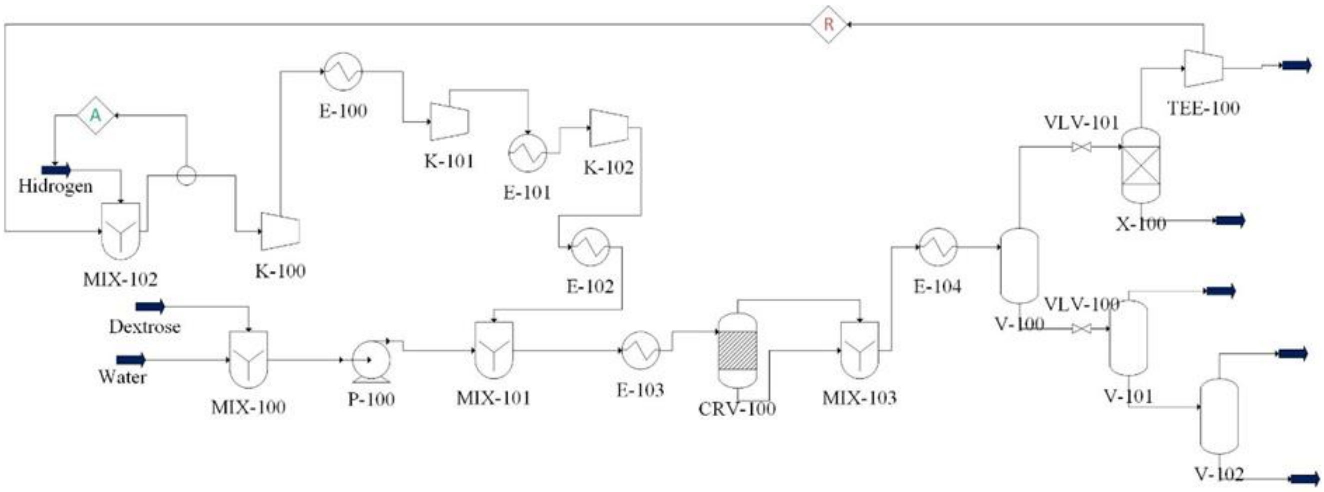


Figure 2. Process flow diagram for basic process of sorbitol production

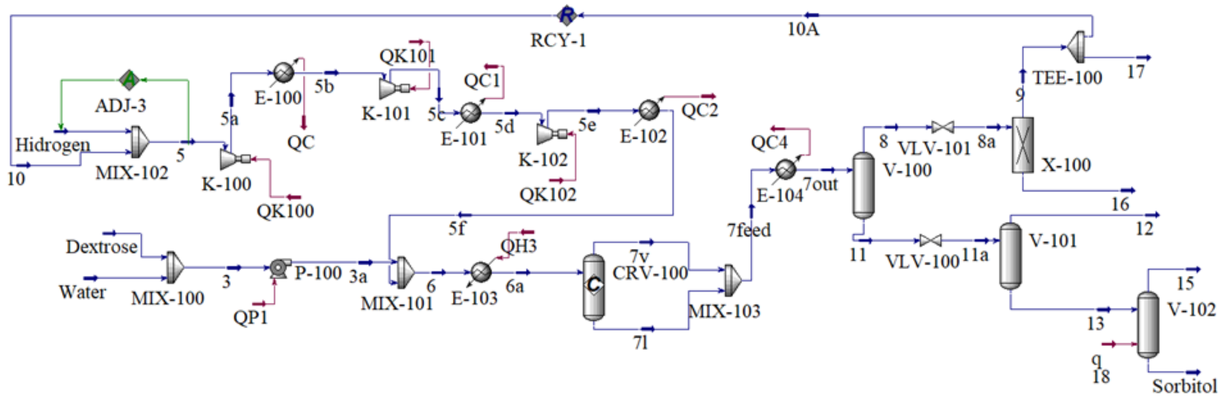


Figure 3. HYSYS simulation of the basic process of sorbitol production.

In addition to that stage, the use of a heat exchanger can be applied to raise the temperature of the dextrose solution output from heat exchanger (E-10) by utilizing the flow of hydrogen from the compressor (K-102). The H_2 flow releases its energy to the dextrose fluid flow, allowing the elimination of a heater before entering the reactor. Then, for other energy efficiency purposes, the hydrogen flow before entering the cooler (E-101) is cooled with the mixed fluid output from the mixer (M-104) in the heat exchanger (E-102). This is aimed at reducing the workload on the cooler (E-101).

3.3 Comparison of Energy Efficiency after Modified Optimization

There is an effect of increasing energy efficiency during the simulation process before and after modification as simulated in Figures 4 and 5, while Table S1 (Supporting Information) shows mass and energy balance of the HYSYS simulation of the modified process. Table 3 compares energy before and after modification to show the energy optimization. It is known that the amount of heat flow in the simulation before and after modification has decreased, which shows considerable energy efficiency. In addition to less energy used, this also indirectly reduces the number of tools used such as pumps and heaters. For comparison, the Specific Energy Consumption (SEC) value can be used as a reference to calculate energy efficiency. In the production of sorbitol with a capacity of 50,000 tons/year, the specific energy consumption is summarized in Figure 6.

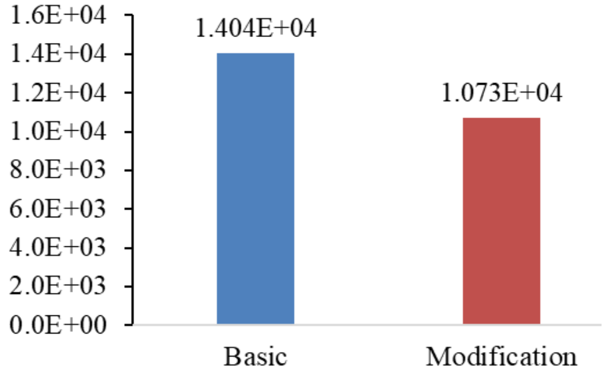


Figure 6. Specific energy consumption of 50,000 tons/year sorbitol production capacity.

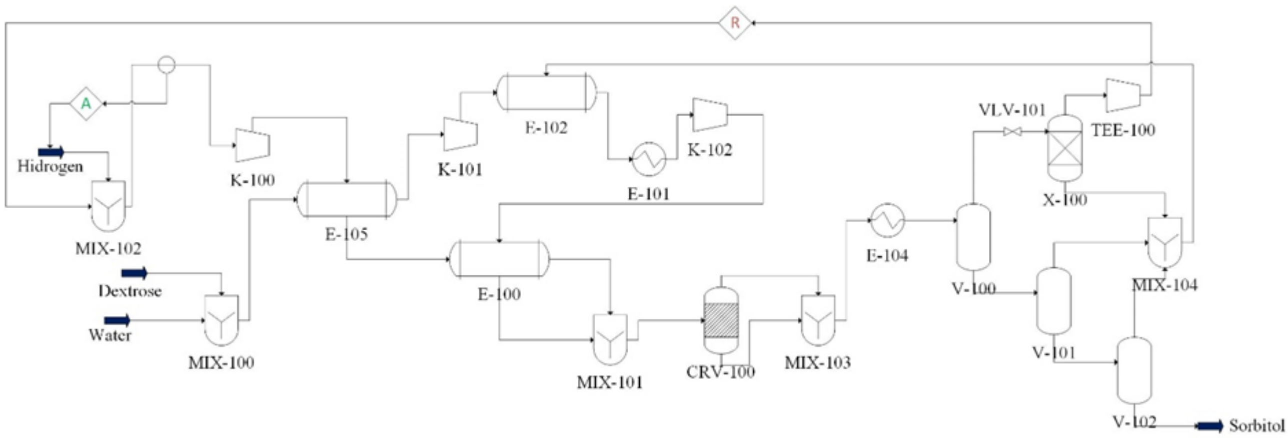


Figure 4. Process flow diagram for modified process of sorbitol production

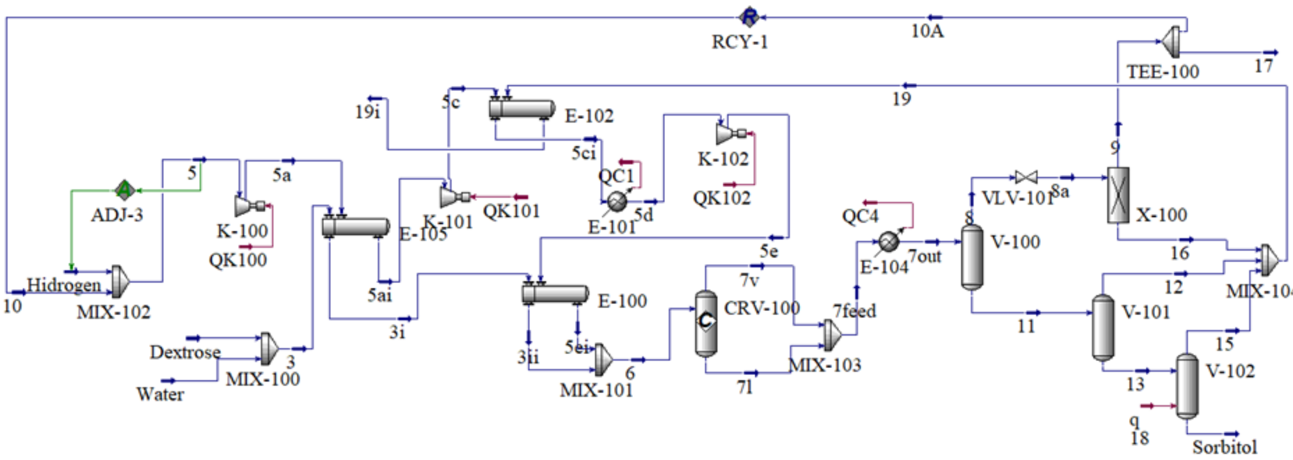


Figure 5. HYSYS simulation of the modified process of sorbitol production.

Table 3. Comparison of energy before and after modification to show the energy optimization.

Unit	Basic (kJ/h)	Modification (kJ/h)
QP1	9.994E+04	-
QK100	1.043E+07	1.946E+07
QC	9.493E+06	-
QK101	1.090E+07	6.164E+06
QC1	8.191E+06	1.577E+07
QK102	1.236E+07	2.750E+06
QC2	8.958E+06	-
QH3	1.753E+06	-
QC4	8.904E+06	8.523E+06
q18	8.724E+06	8.331E+06
TOTAL	7.982E+07	6.099E+07

4. Conclusion

The results of the simulations carried out by modifying the operating conditions with Ru/ASMA@AC and the use of heat exchangers proved to increase energy efficiency significantly. The efficiency achieved is proven by the Specific Energy Consumption value of 3.312E+03 kJ/ton. This is also evidenced by the reduced performance of the compressor and coller. Utilization of fluid heat from one unit to another with the help of a heat exchanger is highly recommended because it reduces wasted heat and reduces costs.

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