

Improving Heat-Exchange Network Efficiency Through Front-End Process Modification in the Drying Oil Production from Acetylated Castor Oil

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Abstract

Enhancing the energy efficiency of drying oil production is critical for reducing utility consumption and advancing process sustainability. This study explores front end heat integration modifications by replacing the fired heater with a process to process heat exchanger and employing the high-temperature bottom stream of the distillation column as an internal heat source. Comparative simulations using Aspen HYSYS V11 were performed for both the baseline and modified flowsheets. The redesigned system enables internal preheating through mixing and heat recovery, thereby eliminating the fired heater and lowering the cooling demand in downstream units. Consequently, the total net energy requirement decreases from 8.895×10^6 kJ/h to 7.363×10^6 kJ/h, corresponding to an efficiency gain of approximately 17.2%, while maintaining product purity at 99.97%. These results highlight the effectiveness of early stage heat integration strategies in reducing external utility demand, improving energy efficiency, and supporting more sustainable drying oil production. Future research may extend to comprehensive heat exchanger network (HEN) optimization and renewable-assisted heat recovery schemes.

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Keywords: Heat-Exchange Network; Front-End Process Modification; Drying Oil; Heat Integration; Energy Efficiency

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1. Introduction

Heat-exchange networks (HENs) are central to improving energy efficiency in drying oil production from acetylated castor oil, a process that requires substantial thermal energy for feed preheating, reaction initiation, and product purification [1]. The extensive use of fired heaters and cooling utilities results in high energy consumption, increased operating costs, and elevated environmental impact. In addition, industrial HENs commonly experience performance degradation due to fouling and

limited operational flexibility arising from feedstock variability [2].

Conventional HEN optimization strategies generally focus on network retrofitting or topology redesign using pinch-based or mathematical optimization approaches [3]. Although effective, these methods are often capital-intensive and disruptive to existing plant operations. Consequently, front-end process modification has gained attention as a practical alternative, emphasizing early-stage adjustments to stream routing, equipment configuration, and operating conditions. This approach enables internal heat recovery with minimal structural changes and can be combined with advanced monitoring and renewable energy integration [4].

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Recent studies have shown that integrating high-temperature internal process streams as heat sources can significantly reduce external utility demand while maintaining product quality and process reliability [5]. In drying oil production, the bottom stream of the distillation column contains substantial recoverable thermal energy; however, in conventional designs this heat is commonly dissipated through cooling prior to recycle, leading to inefficient energy utilization. Improving internal heat recovery supports industrial decarbonization targets and energy-efficiency mandates promoted by global energy policies [6]. In addition, reducing dependence on fired heaters contributes to lower fossil fuel consumption and improved compliance with environmental and sustainability regulations in the chemical industry [7].

The objective of this study is to enhance the energy efficiency of drying oil production through front-end heat integration by eliminating the fired heater and maximizing internal heat recovery. This work evaluates the replacement of the fired heater with a process-to-process heat exchanger and the direct utilization of the high-temperature distillation bottom stream for feed preheating. Comparative simulations of the base-case and modified flowsheets were conducted using Aspen HYSYS V11 to quantify changes in net energy consumption and product purity, thereby providing a clear assessment of the effectiveness of the proposed modification [8].

2. Methods

2.1 Process Simulation using HYSYS

The use of process simulation software has made a significant contribution to the development of chemical engineering curricula in recent years, as it enables more efficient plant design and operation [9]. Aspen HYSYS is one of the most widely used commercial simulators in industry, particularly for conceptual design, process control, optimization, and monitoring at various stages of project development [10]. In general, process simulators function as engineering tools capable of performing automatic calculations, including mass and energy balances, property estimation, design and rating calculations, cost evaluation, and operational optimization. Moreover, simulators provide models that represent various types of reactors and unit operations and are equipped with numerical techniques to solve large-scale algebraic and differential equation systems.

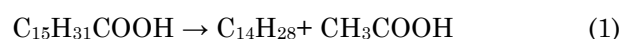
In this study, Aspen HYSYS V11 was employed to simulate the production process of Drying Oil (DO). The software offers an interactive flow diagram that facilitates the construction, review, and management of large-

scale simulations. Aspen HYSYS also provides flexible unit operation modelling, covering distillation columns, reactors, heat transfer equipment, rotating machinery, control systems, and logical operations, which can be applied in both steady-state and dynamic modes. In addition, the software is equipped with a comprehensive thermodynamic database, allowing accurate and consistent calculations of physical properties, transport properties, and phase behaviour [11].

2.2. Drying Oil Production

According to Turton [12], the production of drying oil occurs through a thermal reaction in which acetylated castor oil (ACO) undergoes decomposition and structural rearrangement, producing drying oil (DO) as the main product. DO is widely used in coatings, varnishes, and paints due to its ability to form a hard and stable film layer. In this unit, ACO is converted into DO through a thermal reaction without a catalyst, with acetic acid as a by-product. However, unwanted side reactions may produce gum (heavy polymers). For modelling purposes, ACO is represented as palmitic acid (C₁₅H₃₁COOH), DO as tetradecane (C₁₄H₂₈), and gum as octacosane (C₂₈H₅₆).

The main reaction for the formation of drying oil is written as follows:



Meanwhile, the side reaction that produces gum is written as:



The calculation of reaction heat (ΔH_f°) is used to determine whether a reaction is endothermic or exothermic. The formation of drying oil from acetylated castor oil occurs at a temperature of 25 °C (298 K). The formula for calculating reaction heat is presented as follows:

$$\begin{aligned} \Delta^\circ H_{f(298\text{K})} &= \Delta H_f^\circ(\text{product}) - \Delta H_f^\circ(\text{reactant}) \\ \Delta^\circ H_{f(298\text{K})} &= \Delta H_f^\circ(\text{C}_{14}\text{H}_{28}) + \Delta H_f^\circ(\text{CH}_3\text{COOH}) \\ &\quad - \Delta H_f^\circ(\text{C}_{15}\text{H}_{31}\text{COOH}) \\ \Delta^\circ H_{f(298\text{K})} &= (-207.3 + (-432.3)) - (-723) = \\ &83.4 \text{ kJ/mol} \end{aligned} \quad (3)$$

From the calculation, a positive ΔH_f° value was obtained, indicating that the reaction is endothermic.

Both reactions occur in a tubular reactor filled with inert material to enhance radial mixing. ACO conversion takes place at high temperatures without a catalyst. The main reaction is endothermic and proceeds through

bond cleavage in the ACO molecule. In contrast, gum formation becomes more dominant at higher temperatures due to its higher activation energy. Therefore, temperature control is crucial to suppress polymeric by-products and maintain product quality [12].

The reactor effluent is rapidly cooled (quenching) to stop further reactions and minimize gum formation. The gum formed is removed by filtration before the product stream enters the purification stage. The process generally operates at high temperatures, around 300–400 °C, under near-atmospheric pressure since the reaction is not pressure-sensitive. Unreacted ACO is separated in the purification unit and recycled to improve raw material efficiency. Proper temperature control and effective removal of polymeric by-products are essential to maintain selectivity toward drying oil and ensure long-term reactor stability [12].

2.3. Basic Process Flow Diagram from Literatures

Turton, in his book, designed a process simulation to produce drying oil (DO) in Unit 500 using acetylated castor oil (ACO) as the feedstock. The vapor–liquid phase properties in the simulation were calculated using the Peng–Robinson equation of state, a modification of the Redlich–Kwong equation introduced by Peng and Robinson in 1976. The PR equation requires only the critical properties of pure components for its application, owing to its simple form and the ease with which parameters can be adjusted for multicomponent mixtures [12].

As shown in Figure 1, the production process of drying oil begins with mixing fresh ACO and recycled ACO in a storage tank. The mixture is then pumped to heater H-101 to reach the reaction temperature. The reaction takes place in reactor R-501 without a catalyst, as it is initiated at high temperature. The reactor effluent is cooled using heat exchanger E-101 to stop the reaction, and the gum formed is separated through a filtration unit. The filtrate is subsequently collected alternately in vessel V-102 to maintain continuous flow to Stream 7.

The reaction kinetics follow equations adapted from Smith:

$$-r_1 = k_1 C_{ACO} \tag{3}$$

$$-r_2 = k_2 C^2_{DO} \tag{4}$$

with rate constants:

$$k_1 = 5.538 \times 10^{13} \exp(-44,500/RT) \tag{5}$$

$$k_2 = 1.55 \times 10^{26} \exp(-88,000/RT) \tag{6}$$

The reaction products are directed to distillation column T-101 to separate ACO, which is recycled back into the process. Further purification of drying oil is carried out in column T-102, where acetic acid is removed as a by-product. The final stream, consisting of drying oil and acetic acid, is subsequently cooled prior to storage [12].

2.4. Heat Integration Strategy for Improving Energy Efficiency

Heat integration in chemical processes aims to improve energy efficiency by reusing heat from process streams. Heat exchangers enable indirect

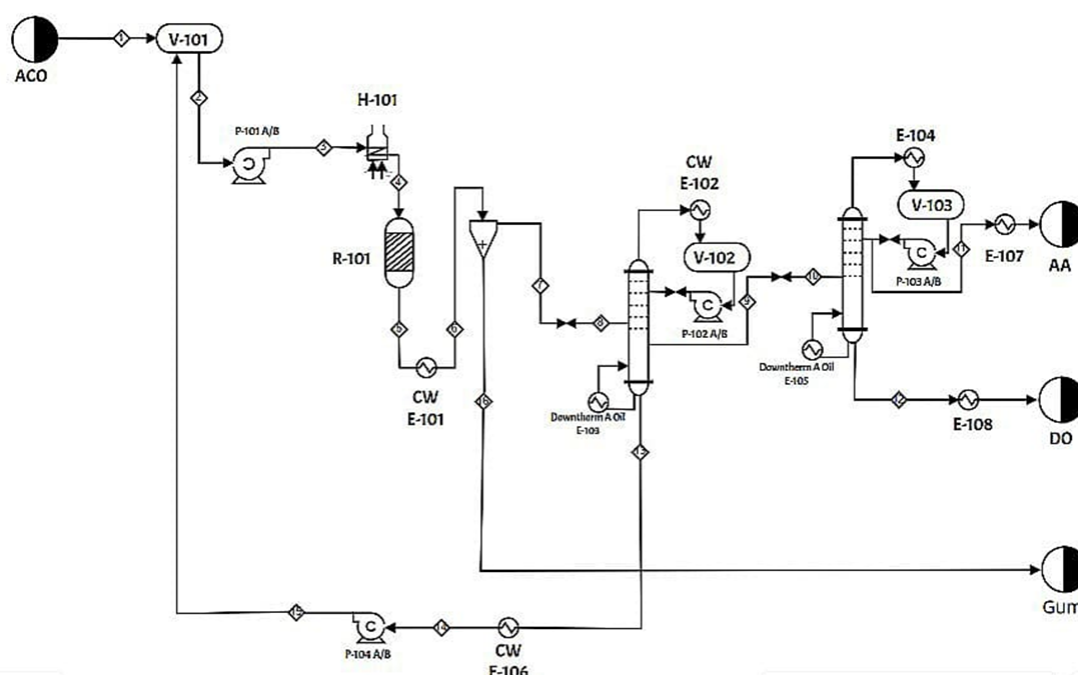


Figure 1. Process Flow Diagram (PFD) of unmodified process [15].

heat transfer between fluids, allowing energy that would otherwise be wasted to raise the temperature of another stream [13]. In drying oil production, the distillation unit generates a high-temperature stream, but in the basic configuration most of this heat is released through a cooler before the recycle process occurs. Consequently, the potential for internal heat utilization remains suboptimal [14].

In the initial configuration (base case), the high-temperature distillation output is cooled using cooler E-106 before being directed to the pump and recycled. After passing through the mixer, the recycle stream is combined with fresh ACO feed, forming a mixture that enters the tubular reactor (R-101). This mixture is then heated by the fired heater (H-101). The entire temperature increase from post-mixer to reaction operating conditions relies solely on the fired heater's thermal energy. This setup results in high fuel consumption and greater utility energy demand, while the heat from the cooler is released to the environment without being utilized.

In the modified design (Figure 2), heat integration is achieved by eliminating the initial cooling of the distillation stream. The hot distillation output is directly recycled and mixed with fresh ACO feed in the mixer, thereby increasing the mixture temperature without external energy input. Before entering R-101, the ACO mixture is heated using heat exchanger E-100, which utilizes heat from another higher-temperature process stream. With this scheme, the fired heater is no longer required, as all preheating needs of the ACO mixture entering

the reactor are met by the internal heat exchanger network.

The working principle of a heat exchanger enables feed heating without additional external energy. Heat is transferred from a high-temperature fluid to a low-temperature fluid through temperature differences and heat transfer rates across the exchanger surface [15]. This mechanism differs from conventional fired heaters, which require fuel as an external energy source. In fired heaters, heat is generated through combustion that converts the chemical energy of fuel into thermal energy, making performance highly dependent on combustion efficiency and operating temperature requirements [16].

When an electric heater is used, heating occurs through the principle of Joule Heating, which is the conversion of electrical energy into heat due to electrical resistance as current flows through a material [17]. This phenomenon is expressed by Joule's law:

$$Q = I^2 \times R \tag{7}$$

Meanwhile, coolers also require utility energy, typically in the form of cooling water or refrigerant, to reduce the process stream temperature [18]. The greater the fraction of heat transferred through process-to-process heat exchangers, the smaller the energy load that must be handled by the cooler.

The implementation of heat integration strategy in E100 during the drying oil process significantly improves energy efficiency. Utilizing internal heat from the distillation stream reduces

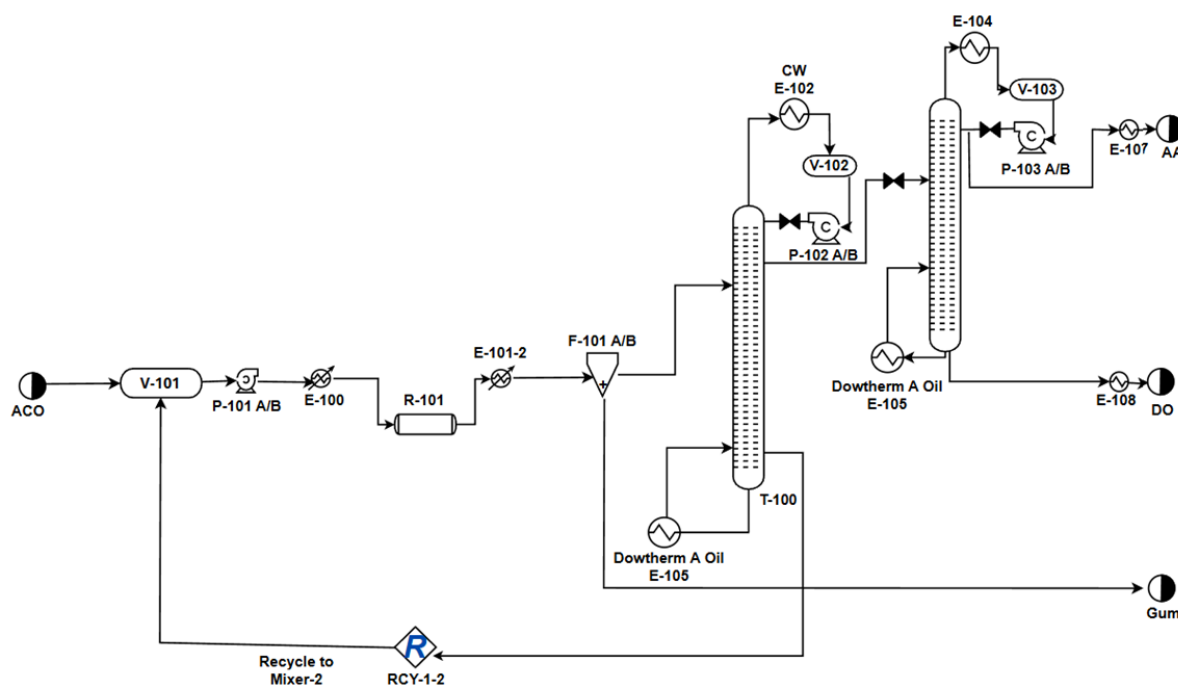


Figure 2. Process Flow Diagram (PFD) of modified process.

fuel consumption in the fired heater (base case), lowers cooling water demand, and ultimately enhances the overall energy efficiency of the unit.

A comparison of the heat efficiency between the basic and modified processes is made using the net energy calculation described below.

$$NE = E_p - E_c \quad (8)$$

Where, NE indicates the net energy (kJ/h), with E_p representing energy generation and E_c representing energy consumption (kJ/h) [14]. This study evaluates how the applied modification affects overall process performance.

3. Results and Discussion

3.1. Comparison Between Basic and Modified Process

Figure 3 illustrates the Aspen HYSYS simulation of the basic process flowsheet, where the feed stream is heated primarily using a fired heater (FH-100) prior to entering the reactor. In this configuration, high-temperature energy from the distillation bottom stream is dissipated through cooling utilities, resulting in higher external energy demand. In contrast, Figure 4 presents the modified process configuration, in which internal heat integration is applied by utilizing the hot distillation bottom stream as a

preheating source for the feed. The fired heater is eliminated and replaced by a process-to-process heat exchanger (E-100), leading to reduced external utility consumption.

3.2. Evaluation of Net Energy Efficiency of the Modified Process

In this study, the heat transfer system was optimized by replacing the fired heater with a heat exchanger (E-100) and redirecting the thermally rich feed stream (BLO-2) to the mixer (MIX-100) as an energy source for the initial feed. This modification resulted in a significant reduction in total net energy consumption. As shown in Table 1, the net energy requirement decreased from 8.895×10^6 kJ/h in the original process to 7.363×10^6 kJ/h in the modified process, representing an energy savings of approximately 17.2%.

The reduction is mainly attributed to the elimination of the fired heater (FH-100) and the recovery of thermal energy from the hot BLO-2 stream via the heat exchanger. By harnessing internal process heat to preheat the feed stream, the reliance on external heating utilities was minimized, thereby lowering the overall energy demand and enhancing the net energy efficiency of the process.

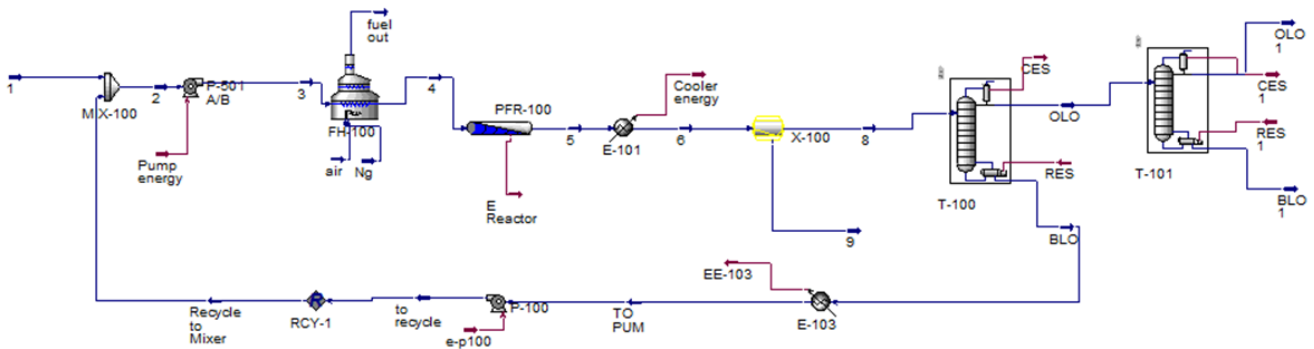


Figure 3. Aspen HYSYS simulation of the basic process.

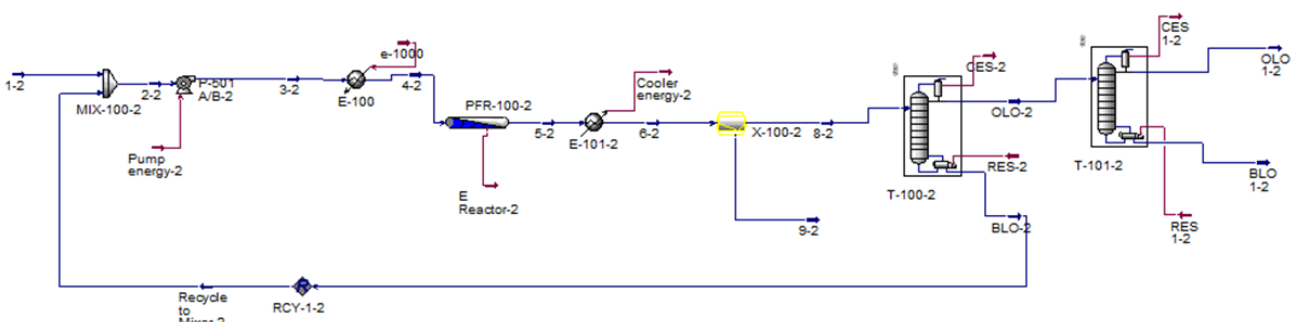


Figure 4. Aspen HYSYS simulation of the modified process.

3.2.1 Heater energy utilization effect

To reach reactor operating conditions, the feed stream must be at approximately 340 °C. Before entering the reactor, the feed is heated in the fired heater (FH-100) to about 250 °C. This stage requires significant energy due to the temperature rise from 25 °C to 250 °C. To improve heat efficiency, the feed stream is mixed with a hot stream from the bottom of the distillation column (T-100). Utilizing the recycled heat from T-100 through the mixer enables internal preheating, thereby eliminating the need for prior cooling with the cooler (P-100).

Through heat integration, the total energy consumption is reduced. As shown in Table 1, the energy required to heat the feed to the reactor (E-Reactor) decreases, while the cooling unit (E-103) no longer requires an energy supply since its cooling load has been eliminated by utilizing recycled heat.

3.2.2 Replacement of the Fired Heater with a Heater

The replacement of the fired heater (FH-100) with heater (E-100) in the initial stage of the process significantly improves energy efficiency and operational safety. In the unmodified scheme, the main feed heating to the reactor is carried out using a fired heater, which requires a large external energy supply. In contrast, in the modified scheme, process heat is recovered through heat recovery, thereby reducing external energy consumption.

In the modified configuration, the process stream from the distillation column (T-100), BLO, at about 360 °C is utilized as a heat source through mixing in the mixer unit (MIX-100). This hot fluid releases part of its energy, lowering its temperature from approximately 350 °C to 250 °C, while the released heat is used to raise the temperature of the reactor feed (stream 1). This

heat recovery reduces the heating load that was previously borne entirely by the fired heater.

Utilizing heat from the process stream reduces the external energy required to reach the reactor's operating temperature compared to the initial configuration. HYSYS simulations indicate that under the modified condition, the stream exhibits a more stable temperature profile before entering PFR-100 and requires significantly less additional heating than a single fired heater. This system not only improves energy efficiency but also reduces risks associated with fired heater use, such as fire hazards and fuel consumption.

By implementing the heater (E-100) and eliminating the cooler (E-103), internal heat utilization is improved, external energy consumption is reduced, and the heating system becomes safer and more efficient compared to the initial configuration that relied entirely on the fired heater.

4. Conclusion

This study successfully enhanced the drying oil production process through the implementation of heat-integration strategies at the front-end section of the flowsheet. By replacing the fired heater with a process-to-process heat exchanger and utilizing the thermal energy available in the hot distillation outlet, the modified design achieved a substantial reduction in net energy consumption from 8.895×10^6 kJ/h in the unmodified configuration to 7.363×10^6 kJ/h, representing an improvement of approximately 17.2%. Importantly, this reduction was accomplished while maintaining the final drying oil purity at 99.97%, indicating that the energy optimization strategy did not compromise product quality. The results demonstrate the effectiveness of internal heat recovery in reducing utility demand and improving overall process efficiency. These findings highlight the significant potential of energy-integration approaches for developing more sustainable and economically competitive production of drying oil. Future research may investigate broader heat-exchange network optimization, incorporation of renewable energy sources, and techno-economic assessment to further strengthen process sustainability.

CRedit Author Statement

Author Contributions: D.P. Soebiakto: Conceptualization, Methodology, Software, Validation, Formal Analysis, Data Curation, Resources, Investigation, Writing, Review and Editing; I.H. Sabrina: Methodology, Software, Validation, Formal Analysis, Data Curation, Resources, Investigation, Writing, Review and Editing; Alfinurazizah: Methodology, Software, Validation, Formal Analysis, Data Curation,

Table 1. Total net energy of overall process.

Energy stream	Basic process energy (kJ/h)	Modified process energy (kJ/h)
Pump energy	768.2	905.8
E reactor	-1.130e6	-1.112e6
Cooler energy	2.889e6	2.912e6
E-103	1.339e6	-
e-p100	87.15	1.673e6
CES	9.243e5	9.214e5
RES	2.114e6	2.151e6
CES 1	2.152e5	2.140e5
RES 1	6.059e5	6.029e5
Total energy stream	8.895e6	7.363e6

Resources, Writing, Review and Editing; A.K. Ahmad: Software, Visualization, Validation; V.F.T.P. Chrisnanto: Software, Visualization; H. Ramadhani: Validation, Formal Analysis. All authors have read and agreed to the published version of the manuscript.

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