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Research Article

Minimizing Net Energy Consumption in Vinyl Chloride Monomer (VCM) Production using Heat-Integrated Process Design

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Abstract

Vinyl chloride monomer (VCM) is a key intermediate in polyvinyl chloride (PVC) production, and its manufacture via thermal cracking of 1,2-dichloroethane (EDC) is highly energy intensive. This study aims to reduce the net energy demand of the EDC–VCM section through a heat-integrated process design. A steady-state simulation of the conventional EDC cracking and distillation train was developed as an industrial benchmark. Based on this model, a modified configuration was introduced by adding a feed–effluent heat exchanger to recover heat from the hot reactor effluent and preheat the combined fresh and recycled EDC feed, while maintaining reactor operating conditions and product specifications. Energy performance was evaluated by comparing heating and cooling duties of major equipment. The heat-integrated design lowered the total utility requirement from 9.39×10^7 to 7.93×10^7 kJ/h, equivalent to a 15.5% reduction in external energy demand and reducing total energy cost by 4.3%. These results demonstrate that a simple heat-exchanger retrofit can significantly improve energy efficiency in VCM production, providing a practical route to reduce utility consumption and operational costs.

Keywords: Vinyl Chloride; EDC cracking; energy efficiency; net energy; 1,2-dichloroethane

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1. Introduction

Rapid growth across various industries in Indonesia, particularly the petrochemical sector, is fueled by rising demand for polymer-based materials driven by advancements in construction, manufacturing, and infrastructure development. This trend has intensified the need for polyvinyl chloride (PVC), a versatile polymer widely utilized in cables, pipes, construction components, and household products [1]. Consequently, the escalating demand for PVC directly increases the requirement for vinyl chloride monomer (VCM), its primary feedstock. However, VCM is classified as a hazardous carcinogen and poses significant health risks to workers exposed to it in industrial environments [2]. Therefore, ensuring the efficient and sustainable availability of VCM is crucial to support both industrial and domestic needs, while simultaneously safeguarding worker health and promoting long-term process sustainability.

Vinyl chloride monomer (VCM) is an organic compound with the molecular formula C_2H_3Cl, widely recognized as the primary feedstock for polyvinyl chloride (PVC). In industrial practice, VCM is predominantly produced from 1,2-dichloroethane (EDC), which is synthesized through the reaction of ethylene (C_2H_4) with chlorine (Cl). Modern VCM production is closely integrated with the chlor-alkali process, where chlorine and EDC serve as the principal precursors [3]. Historically, the earliest method employed was the hydrochlorination of acetylene, in which hydrogen chloride reacted with acetylene in the presence of a mercury catalyst. This route

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has since been abandoned due to raw material limitations and severe environmental concerns [4]. Contemporary industry relies on the direct chlorination of ethylene, producing high-purity EDC through the direct reaction of ethylene and chlorine. Conversion to VCM requires a subsequent pyrolysis step, operated at elevated temperatures of 400–500 °C, which consumes substantial energy while yielding both VCM and hydrogen chloride (HCl) [3]. To improve efficiency and resource utilization, the ethylene oxychlorination process has been developed, wherein HCl generated as a pyrolysis byproduct reacts with oxygen to regenerate EDC, thereby enhancing process sustainability [5].

Several researchers have focused on the technological aspects of VCM production, particularly through direct chlorination, ethylene oxychlorination, and pyrolysis of ethylene dichloride (EDC). Their studies highlight that the EDC pyrolysis step represents a critical stage in VCM production, capable of yielding high concentrations of VCM but constrained by its substantial energy requirements due to the extreme operating temperatures involved [3]. In parallel, research on ethylene oxychlorination has explored the utilization of pyrolysis byproducts, especially hydrogen chloride (HCl), to regenerate EDC, thereby improving yield and offering a more economical production route. Building on these insights, there exists a significant opportunity to address the limitations of high energy consumption by integrating a heat exchanger (HE) system. Such integration enables recovery of thermal energy from the hot product stream to preheat the feed, reducing reliance on external energy sources while simultaneously enhancing overall process efficiency.

The primary objective of this study is to minimize the net energy demand in vinyl chloride monomer (VCM) production by applying a heat-integrated process design to the thermal cracking of 1,2-dichloroethane (EDC). To establish an industrial reference, a steady-state simulation model of the conventional EDC cracking and distillation sequence was first developed using Aspen HYSYS. Building upon this baseline, a modified configuration is proposed that incorporates a feed–effluent heat exchanger, enabling recovery of thermal energy from the hot reactor effluent to preheat the incoming EDC feed. The conventional and modified systems are subsequently evaluated and compared in terms of their overall heating and cooling duties, thereby allowing the potential energy savings achieved through heat integration in the VCM section to be quantified with clarity.

2. Methods

2.1 Property Package

The simulation of the Vinyl Chloride Monomer (VCM) production process was performed using Aspen HYSYS software. To accurately predict the thermodynamic properties and phase behavior of the multicomponent system specifically the non-ideal interactions between HCl, EDC, and VCM at high pressures, the Soave-Redlich-Kwong (SRK) equation of state was utilized. The SRK model is widely documented in chemical engineering literature as a robust method for calculating vapor-liquid equilibrium (VLE) in light hydrocarbon and halogenated systems [6]. This selection ensures that the enthalpy and density calculations during the simulation align with experimental data reported in previous studies.

2.2 Energy Optimization using Heat Exchanger

The primary energy optimization strategy focuses on minimizing the thermal duty of the EDC cracking furnace, which is identified as the most energy-intensive unit in the VCM production process. The thermal cracking reaction is typically conducted at high temperatures ranging from 400 °C to 500 °C inside a gas-fired furnace to effectively convert 1,2-dichloroethane (EDC) into vinyl chloride monomer [7]. To mitigate this substantial energy consumption, the process design is modified by implementing a heat integration scheme, specifically the installation of a feed-effluent Heat Exchanger (HE). This unit utilizes the high-temperature sensible heat from the reactor product stream to preheat the incoming EDC feed, thereby significantly reducing the external fuel requirement for the furnace and enhancing the overall thermal efficiency

The effectiveness of this modification is evaluated by performing a comparative analysis of the net energy consumption between the basic (unmodified) process and the modified heat-integrated process using Aspen HYSYS simulation. The analysis quantifies the total heating and cooling duties to determine the potential energy savings. This methodology aligns with recent process optimization studies, which demonstrate that integrating heat recovery systems and optimizing operational parameters are effective methods for reducing both the Total Annual Cost (TAC) and carbon emissions in vinyl chloride production plants [8].

2.3 Calculation and Assessment of Net Energy and Utility Cost

In this study, net energy consumption for the EDC–VCM section is defined as the total external utilities required by the process. For every unit operation in the HYSYS flowsheet, such as heaters, the cracking furnace, reboilers, coolers, condensers and the compressor, the simulator reports a steady-state heat duty $\dot{Q}_j$in kJ/h. Positive values correspond to heat supplied to the process by hot utilities, while negative values represent heat removed by cold utilities. The overall hot-utility demand and cold-utility demand are therefore obtained by summing these duties over all relevant equipment, and the sum of hot and cold utility loads (plus the compressor power expressed on an energy basis) is taken as the net external energy rate of the EDC–VCM section. The mathematical calculation can be done as follow:

$$\dot{E}_{\mathrm{net}} = \dot{Q}_{\mathrm{hot,tot}} + \dot{Q}_{\mathrm{cold,tot}} + \dot{Q}_{\mathrm{el,eq}} \tag{1}$$

The impact of the heat-integration retrofit is then assessed by comparing the net energy of the base and modified configurations and by translating this net energy into annual utility cost, following the general approach used in techno-economic studies of VCM processes [9]. For each configuration, the total heating and cooling duties of heaters, the cracking furnace, reboilers, coolers, condensers and the compressor are taken from Aspen HYSYS and converted into annual net energy consumption using the assumed operating time of 2,560 h per year. This annual net energy is multiplied by unit prices for steam, fuel, cooling water and electricity to obtain the corresponding annual utility cost. In the modified flowsheet, the duty of the additional feed–effluent heat exchanger and any change in heater or furnace duties are included in the same way, so that both net energy and annual energy cost of the base and heat-integrated configurations can be compared on a consistent basis. The modified process is judged to be energetically favorable when its net energy consumption, and therefore its annual energy cost, is lower than that of the base case while the key operating conditions and product specifications remain unchanged.

2.4 Process Overview and Simulation Basis

The simulation of the Vinyl Chloride Monomer (VCM) production process is grounded in the thermal cracking of 1,2-dichloroethane (EDC) within a plug-flow tubular reactor. The core of this pyrolysis unit is the cracking furnace, where the reaction takes place inside a long empty coil suspended within a radiation chamber. The cracking process is characterized as a highly endothermic gas-phase reaction that converts EDC into VCM and hydrogen chloride (HCl). Due to the endothermic nature of the reaction, significant heat input is required along the reactor length to maintain the necessary reaction kinetics and achieve the desired conversion rates [10].

Following the reaction stage, the reactor effluent undergoes rapid cooling before entering the separation train to isolate the purified VCM. The purification process typically involves a sequence of distillation columns: a low-boiling tower is first employed to remove light impurities such as acetylene, followed by a high-boiling tower designed to separate the heavy components, primarily unreacted EDC, from the final VCM product. Recent simulation studies demonstrate that optimizing the parameters of these distillation units is essential for minimizing the Total Annual Cost (TAC) and reducing carbon dioxide (CO_2) emissions while maintaining high product purity [8].

3. Results and Discussion

3.1 Thermodynamic Review

Thermodynamic evaluation plays a key role in defining suitable operating conditions for reaction-based processes in the chemical industry. By determining the reaction enthalpy (ΔH_r), Gibbs free energy (ΔG_r), and equilibrium constant (K), it becomes possible to identify whether a reaction behaves exothermically or endothermically and to judge the extent of its reversibility and equilibrium constraints [11]. These insights are central to the design of efficient and sustainable plants, since they support the choice of temperature, pressure, and feed composition that maximize product yield while reducing energy demand. In this study, the thermodynamic characteristics of the EDC cracking reaction are analyzed using the standard enthalpy and Gibbs free energy of formation ($\Delta H^{o}_{f,298K}$ and $\Delta G^{o}_{f,298K}$) of each compound, as listed in Table 1.

The value of cracking of EDC process can be presented by the reaction below:

$$C_2H_4Cl_2 \rightarrow C_2H_3Cl + HCl \tag{2}$$

Where the value of $\Delta H^{o}_{r\ 298K}$ can be calculated by:
$\Delta H^{o}_{r\ 298K} = \Sigma\Delta H^{o}_{f,product} - \Sigma\Delta H^{o}_{f,reactant}$
$\Delta H^{o}_{r\ 298K} = (\Delta H^{o}_{f}\ C_2H_3Cl + \Delta H^{o}_{f}\ HCl) - (\Delta H^{o}_{f}\ C_2H_4Cl_2) = +\ 63.0$ kJ/mol

Table 1. The value of ΔH^{o}_{289K} and ΔG^{o}_{289K} of compounds (kJ/mol) [12].

Compounds	$\Delta H^{o}_{(289K)}$	$\Delta G^{o}_{(289K)}$
$C_2H_4Cl_2$	-126.8	-70.2
HCl	-92.3	-228.6
C_2H_3Cl	28.5	41.1

Based on the calculations, the resulting value is positive, which indicates that the reaction absorbs heat from its surroundings and can therefore be classified as endothermic. Furthermore, the value of $\Delta G^o_{r\ 298K}$ can be calculated as follow:

$\Delta G^o_{r\ 298K} = \Sigma\Delta G^o_{f,product} - \Sigma\Delta G^o_{f,reactant}$ (2)
$\Delta G^o_{r\ 298K}$ = $(\Delta G^o_f\ C_2H_3Cl + \Delta G^o_f\ HCl) - (\Delta G^o_f\ C_2H_4Cl_2)$ = – 117.3 kJ/mol

The ΔG°_r obtained is negative, meaning that the reaction is thermodynamically favorable and can be classified as spontaneous under standard conditions. The value of equilibrium constant (K) at 298 K (25°C) can be calculated by:

$$\Delta G^\circ = -RT\ln K_2$$
$$\Delta G^\circ_{298} = -117.3\ \text{kJ/mol}$$
$$\ln K_{298} = -\frac{\Delta G^\circ_{298}}{RT} = -\frac{-117.3\times10^3}{8.314\times298} \approx 47.34$$
$$K_{298} \approx 3.6\times10^{20}$$

Equilibrium constant (K_1) at reactor temperature T = 500 °C:

$$\ln\frac{K_1}{K_2} = -\frac{\Delta H^\circ_R}{R}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)$$
$$\ln\frac{K_1}{3.64\times10^{20}} = -\frac{63.0\times10^3\ \text{J/mol}}{8.314\ \text{J/(mol·K)}}\left(\frac{1}{773\ \text{K}}-\frac{1}{298\ \text{K}}\right)$$
$$K_1 = 2.2\times10^{27}$$

At the reactor operating temperature of 500 °C (773 K), the equilibrium constant becomes extremely large, $K_{773} = 2.2\times10^{27}$, indicating that the cracking of EDC to VCM and HCl is overwhelmingly product-favoured. In practice this means the reaction can be treated as essentially irreversible, and process design is controlled mainly by kinetics and heat supply rather than equilibrium limitations [13].

3.2 Basis Production of Vinyl Chloride Monomer

The VCM production scheme is shown in Figure 1 and 2, adapted from industrial process descriptions for EDC/VCM plants. In this process, purified 1,2-dichloroethane (EDC) is converted to vinyl chloride monomer (VCM) by thermal cracking. Fresh EDC from the purification section is blended with recycled EDC from the separation section in mixer M-210A to form a single, stable feed stream that is preheated in heater E-100 and compressed in compressor K-100 to a cracking pressure of about 3 MPa. The compressed vapor is then heated to a typical cracking temperature of around 500 °C before entering the cracking reactor CRV-100, where gas-phase pyrolysis produces a mixture of VCM, hydrogen chloride (HCl), unreacted EDC, and heavy by-products. Computational and industrial studies show that

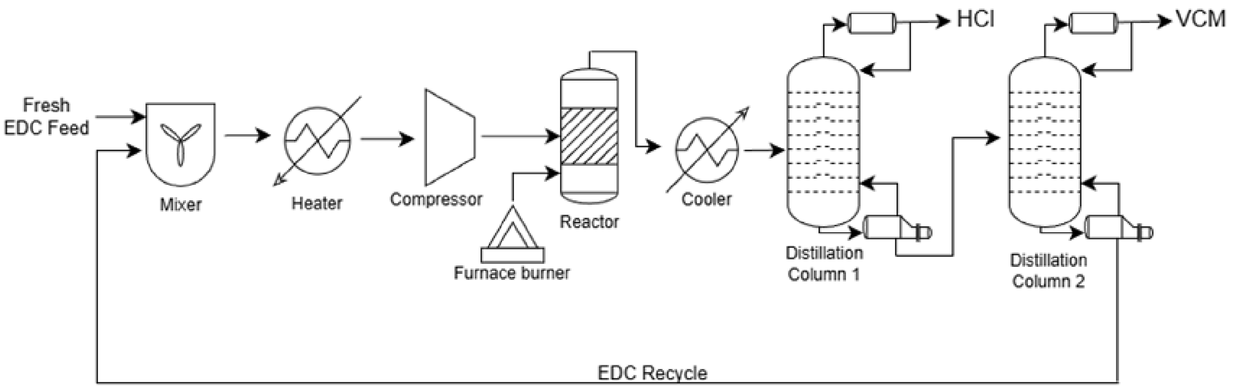

Figure 1. Process flow diagram of basic VCM production process by thermal cracking [17].

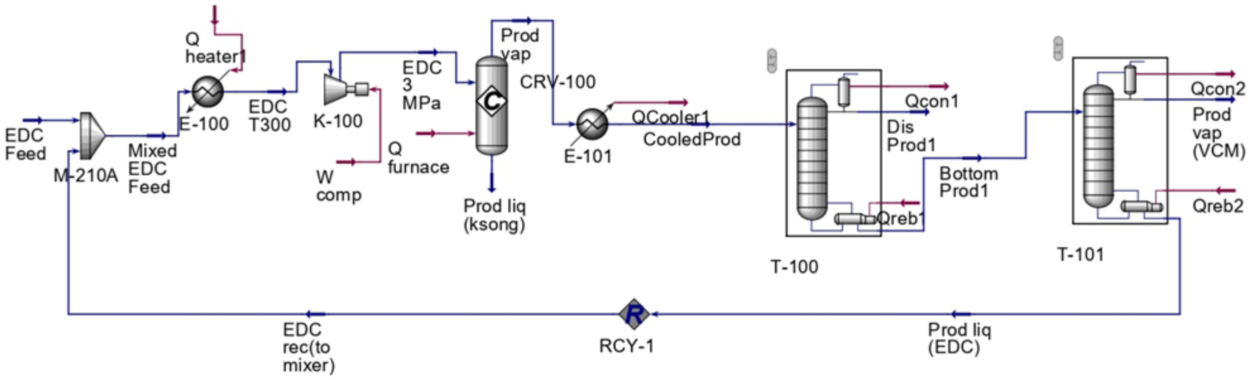

Figure 2. Process simulation using Aspen HYSYS of basic process of VCM production by thermal cracking HYSYS simulation [17].

EDC cracking is a strongly endothermic, high-activation-energy reaction, so a high inlet temperature is required to achieve sufficient conversion and selectivity; increasing the feed temperature raises the Arrhenius rate constant and allows the coil to supply the necessary heat along its length. This behavior has been demonstrated in detailed CFD simulations and plant data for commercial cracking furnaces [14,15]

The hot reactor effluent is routed to a cooler (E-101) to quench the gas, reduce its temperature, and partially condense the chlorinated organics, producing a two-phase stream that feeds the first distillation column (T-100). Consistent with typical VCM plants, this first column mainly removes HCl and light ends overhead, while a bottom stream rich in VCM and EDC is obtained. Licensor descriptions of commercial VCM units describe this separation in terms of an HCl or “acid gas” column followed by a VCM column that handles only organic chlorides. The VCM–EDC mixture from the bottom of T-100 is then fed to a second distillation column (T-101), which acts as the VCM/EDC splitter and produces VCM at the top and an EDC-rich liquid at the bottom. Using two columns rather than a single tower is consistent with multicomponent distillation theory, where mixtures that contain a highly volatile, corrosive component (HCl) and two closer-boiling organics are commonly separated in a sequence of columns to improve relative volatility, tray efficiency, and operability [17].

The EDC-rich bottom stream from the VCM/EDC splitter T-101 is returned via a recycle line (RCY-1) to the EDC purification and then back to mixer M-210A. This recycle is essential because single-pass conversion in the cracking furnace is deliberately limited to moderate values to avoid excessive by-product formation and coke deposition; overall yield is therefore maximized by recovering and recycling unreacted EDC. Industrial design reports and patents for VCM production describe the same strategy, where unconverted EDC from the VCM column bottom is routed to EDC distillation and then sent back to the cracking unit, while HCl recovered overhead is returned to the oxychlorination loop to close the chlorine balance work on VCM distillation and heat-exchanger network design also confirms that efficient separation and recycle of EDC are key levers for increasing VCM production rate, improving product purity, and reducing overall energy consumption in EDC/VCM complexes [18].

3.3 Modified Production of Vinyl Chloride Monomer

Based on the HYSYS simulation results shown in Figures 3 and 4, the total energy requirement of the EDC–VCM section can be obtained in the form of heat flow (kJ/h) for each

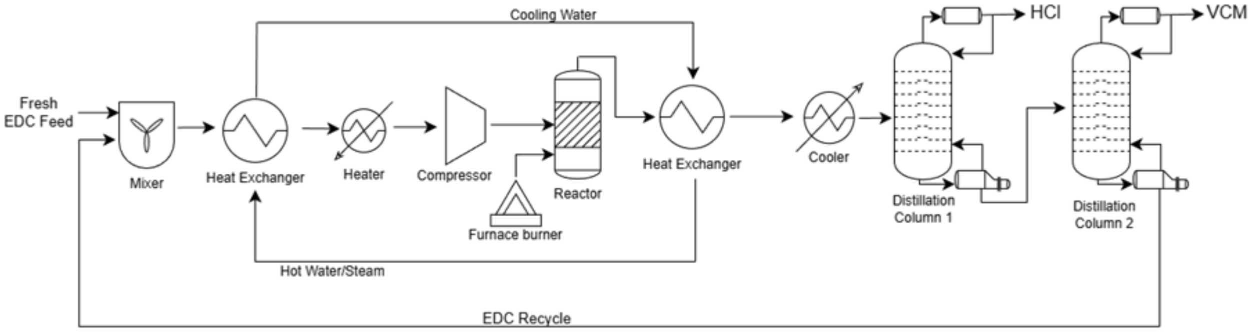

Figure 3. Process flow diagram of modified VCM production process by thermal cracking.

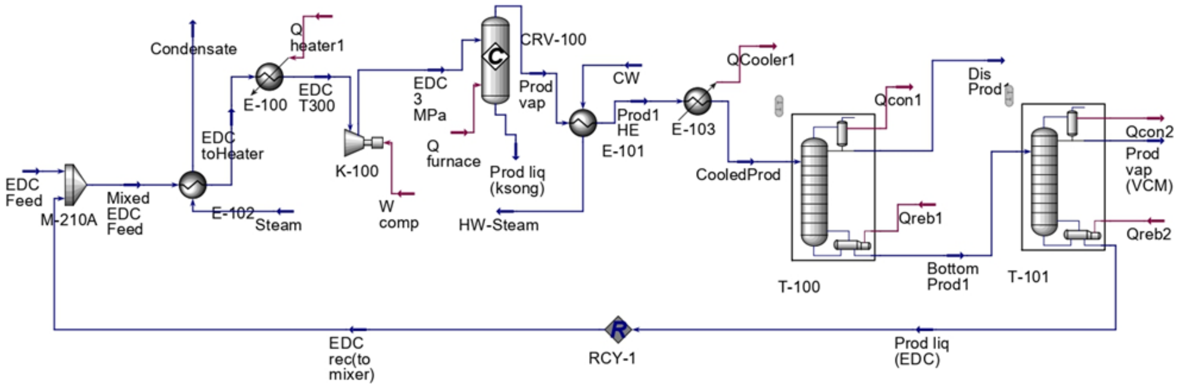

Figure 4. Aspen HYSYS simulation of the modified VCM production process by thermal cracking.

piece of equipment. The individual duties of heaters, reboilers, coolers, condensers, and the compressor provide a consistent picture of how much external heating and cooling the process requires under steady-state operating conditions. Simulation-based energy balances of this kind are widely used in process design and techno-economic assessment to quantify utility consumption and operating cost before plant construction or retrofit, especially for energy-intensive petrochemical processes [19]. These heat-flow data are therefore treated as indicators of utility demand and form the basis for evaluating the effect of the proposed modification to the VCM section.

In the modified flowsheet, an additional heat exchanger is introduced to recover heat from hot process streams and use it to preheat the incoming EDC feed, so that less external heating and cooling are required while the reactor operating conditions and product specifications are maintained. Assessing the difference in heat flows between the base and modified cases is essential, because heat-integration and pinch-analysis methodologies explicitly use changes in hot- and cold-utility duties as the primary metrics for energy-saving potential and operating-cost reduction [20,21]. In line with this approach, the equipment-level heat-flow values generated by the simulation are compiled and summarized in Table 2 to provide a clear comparison of utility demand between the conventional and heat-integrated configurations and to quantify the energy benefit of the proposed retrofit in a manner consistent with previous heat-integration studies.

From Table 2, the total utility duty (heating and cooling) in the unmodified process is 9.39×10^7 kJ/h, whereas in the modified process it decreases to 7.93×10^7 kJ/h. This corresponds to a reduction of approximately 15.5% in overall energy supply to the system. These results indicate that the addition of the heat exchanger successfully lowers the external utility requirement without changing the desired conversion, thereby improving the energy efficiency of the EDC–VCM section and potentially reducing operating costs associated with fuel, steam, and cooling utilities.

3.4 Utility Cost Performance

For an annual operating time of 2,560 h, the HYSYS results show that the base EDC–VCM process requires a total utility cost of about 610,472 USD/year, as summarized in Table 3. In this analysis, the utilities are grouped into three categories, namely heating utilities (furnace plus steam), cooling utilities, and electricity for the compressor. For the base case, heating utilities contribute 310,180 USD/year, cooling utilities 24,025 USD/year, and compressor electricity 276,267 USD/year. After the heat-integration retrofit, where a feed–effluent heat exchanger is added and the heating and cooling loads are redistributed, the total annual energy cost decreases to 583,971 USD/year. This corresponds to a reduction of roughly 20,964 USD/year in heating cost and 5,537 USD/year in cooling cost, while the electricity cost remains unchanged because the compressor duty is not affected.

This reduction in net energy demand translates into a decrease in total utility cost of about 4.3% compared with the base case. Although the percentage reduction in monetary terms is smaller than the 15.5% drop in net energy demand, the trend is consistent: the heat-integrated configuration effectively lowers external utility consumption and converts this into a measurable decrease in annual operating cost without changing the reactor conditions or product specifications.

4. Conclusion

This study developed and evaluated a heat-integrated design for vinyl chloride monomer production via thermal cracking of 1,2-dichloroethane. Thermodynamic analysis

Table 2. Comparison of basic and modified VCM production process.

Process Equipment	Energy Stream	Heat flow (kJ/h)	
		Basis	Modified
K-100	W comp	5546000	5546000
E-100	Q heater 1	15080000	8442000
CRV-100	Q Furnace	16330000	16330000
E-101	Q cooler 1	16470000	11810000
T-100	Q Con 1	23120000	17520000
T-100	Q Reb 1	7510000	9859000
T-101	Q Con 2	5093000	5093000
T-101	Q reb2	4701000	4701000
Total		93850000	79301000
Difference		14549000	

confirmed that the cracking reaction is strongly endothermic yet thermodynamically favorable at reactor conditions, so high operating temperatures are required to overcome the activation barrier while equilibrium does not limit conversion. Steady-state simulation of the conventional EDC–VCM section in Aspen HYSYS showed that the main utility consumers are the furnace, the feed heater and the associated condensers and reboilers. Introducing a feed–effluent heat exchanger to recover sensible heat from the hot reactor effluent and preheat the EDC feed reduced the combined heating and cooling duty from 9.39×10^7 to 7.93×10^7 kJ/h, corresponding to a 15.5% decrease in net external energy consumption at unchanged reactor pressure, temperature and product specifications. When the simulated utilities are grouped into heating, cooling and compressor electricity and converted into annual costs for 2,560 operating hours per year, the total utility expenditure decreases from about 610,472 to 583,971 USD/year, i.e. a reduction of roughly 26,500 USD/year or 4.3% compared to the base case. Overall, these results show that a relatively simple heat-integration retrofit can provide meaningful energy savings and a measurable reduction in utility cost for VCM production without altering the core reaction conditions or product quality.

CRedit Author Statement

Author Contributions: Faith Nadine Rachmantoro: Process simulation methodology, Aspen HYSYS modelling, process investigation, data curation, writing – review and editing. Alya Marsya Talitha: Conceptualization, literature review, writing – original draft preparation, writing – review and editing. Andanafifajri Ahda Maulana: Conceptualization, process scheme development, writing – original draft preparation, writing – review and editing. Chyntami Fredella Sitorus: Overall conceptualization, methodology, quantitative thermodynamic and energy calculations, formal analysis, supervision, writing – review and editing, project administration. All authors have read and agreed to the published version of the manuscript.

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