Integrated Process Design and Economic Evaluation of Waste-to-Biomaterial Conversion: Hydroxyapatite Production from Blue Crab Shells using Aspen Plus

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Abstract
The demand for bone transplant materials is rising in Indonesia. A biogenic calcium supply for hydroxyapatite (HAp), the primary inorganic component of human bone, is provided by blue crab shells, which are produced contain 53.70–78 weight percent $CaCO_3$. A steady-state method for producing HAp from crab shells is developed and assessed in this study, utilizing Aspen Plus V14 in conjunction with the Aspen Process Economic Analyzer. The simulated flowsheet comprises solid–liquid separation, drying/sintering, CaO storage, CaO hydration, HAp precipitation with H_3PO_4. The global thermodynamic model chosen is the SOLIDS property approach, and stoichiometric reactions with Arrhenius-type power-law kinetics are used to simulate HAp production. In the simulation, 150.246 kg·h^{-1} HAp, or roughly 1451.81 t·year^{-1}, is predicted for a design base of 46.48 kg·h^{-1} CaO. A 20-year equipment lifetime, 8000 operating hours annually, a 20% rate of return, and zero-cost shells are assumed in the economic study. This results in a total capital cost of USD 1.94 million and an annual operating cost of USD 1.31 million. The findings offer a quantifiable starting point for evaluating the technical viability of waste-to-HAp systems and directing additional experimental validation, life-cycle analysis, and process improvement.

Keywords: Aspen plus simulation; Calcium carbonate; Crab shell waste; Hydroxyapatite; Techno-economic assessment

1. Introduction

One kind of crab that is frequently found in Indonesian oceans is the rajungan/blue crab shells *(Portunus pelagicus)*. Data from the Ministry of Marine Affairs and Fisheries indicates that 2,747 tons of blue crabs were caught annually in 2022. Because of their high catch volume, blue crabs are now one of the primary export commodities to several nations, including the US, China, Japan, and Singapore [1]. The majority of Indonesian blue crabs are used to make different seafood items. With the waste percentage of the processed crabs reaching 45% of their entire weight, this processing produces a substantial amount of shell waste [2]. Data on crab catches indicate that 1,236.16 tons of shell waste are produced annually. Improper management of this shell trash can lead to major environmental issues.

The community and the environment may gain a lot from the efficient use of crab shell trash, including higher incomes for locals and less environmental harm. Large levels of calcium carbonate ($CaCO_3$), ranging from 53.70 to 78%, are found in crab shells; this is a major potential that is not well understood [3]. Moreover, their chitin content varies from 18.7 to 32.2% and their protein content from 15.6 to 23.9% [4]. Because of this makeup, crab shells have been used extensively as raw materials to produce hydroxyapatite (HAp: $Ca_{10}(PO_4)_6(OH)_2$), chitosan, and edible films [5][6]. From a thermochemical perspective, the crab shell fraction rich in $CaCO_3$ experiences an endothermic decomposition during the calcination process. The chemical reaction that occurs is as follows:

$$CaCO_{3\,(s)} \rightarrow CaO_{(s)} + CO_{2\,(g)} \qquad (1)$$

This reaction typically occurs within a temperature range of approximately 700–905 °C, influenced by factors such as CO_2 partial pressure and heating conditions. It is noted for having relatively high activation energies, as documented in studies focusing on $CaCO_3$ and limestone systems utilized in calcium-looping and similar processes. Consequently, to produce hydroxyapatite products, it is essential to convert calcium carbonate into calcium oxide (CaO), which serves as the primary component in HAp synthesis through the calcination of crab shells. After calcination, the CaO content can reach levels of up to 93.78%, resulting in a substantial yield of HAp [4][7].

The greatest inorganic component of human bones is hydroxyapatite, a naturally occurring type of calcium phosphate. In medical applications, calcium phosphate with a Ca/P atomic ratio of 1.67 is the ideal ratio for natural bones due to its good biocompatibility [8]. Studies on the use of hydroxyapatite (HAp) for bone regeneration demonstrate that HAp has benefits in osteoconductivity, bioactivity, biocompatibility, and the capacity to maintain bone tissue while it grows [9][10][11]. In addition to its superior osteoconductive qualities, hydroxyapatite is non-toxic, non-inflammatory, and has good immunogenicity in both in vitro and in vivo testing [12][13]. Thus, extensive research is currently underway focused on the production of hydroxyapatite for medical applications, particularly utilizing waste materials such as crab shells. From a process-systems viewpoint, these biomedical demands have spurred the development of integrated production pathways for hydroxyapatite that can be modeled in Aspen Plus. This process involves calcining calcium carbonate derived from crab shells to produce CaO or $Ca(OH)_2$, followed by a reaction with phosphoric acid in either stirred or tubular reactors. The subsequent steps include the precipitation and aging of calcium phosphate solids, solid-liquid separation and washing, drying, and, if necessary, sintering. Flowsheets created in Aspen Plus for related calcium-phosphate-water systems, like phosphoric acid and calcium phosphate production, demonstrate that these models can replicate plant operations and provide a quantitative framework for scaling up and optimizing processes [14]. Furthermore, recent experimental investigations consistently underscore the importance of the calcium-to-phosphorus (Ca/P) molar ratio as a key design parameter; ratios approaching the stoichiometric value of 1.67 promote high purity and conversion rates of hydroxyapatite phases. In contrast, a Ca/P ratio below 1.67 may lead to the formation of calcium-deficient apatites or amorphous calcium phosphate, while a ratio exceeding 1.67 frequently results in leftover $CaO/CaCO_3$ or secondary calcium phosphate phases, which can diminish effective yields of hydroxyapatite and negatively impact mechanical and biological properties [15].

The hydroxyapatite synthesis process needs to be completed as efficiently and optimally as possible. To accomplish these outcomes, a suitable method for process design and simulation is required before large-scale manufacturing. Most current research on the production of hydroxyapatite from biogenic calcium sources, such as eggshells and crab shells, predominantly emphasizes laboratory-scale synthesis and material characterization, while providing limited insights into integrated process performance, energy consumption, or scalability. Consequently, there exists a gap in research regarding the transition of these experimental approaches into a comprehensive process flowsheet that incorporates quantified mass and energy balances along with a clear evaluation of sustainability and operational feasibility. Aspen Plus is one of the software tools available for this purpose. It is particularly beneficial for simulating and optimizing various chemical processes due to its ability to produce accurate results at each stage until the desired product is realized, thereby reducing costs associated with research and development in the industry. Previous studies on shell waste valorization have demonstrated that Aspen Plus simulations can enhance experimental findings by identifying optimal operational parameters, conducting sensitivity analyses, and supporting techno-economic as well as environmental assessments at an industrial scale [16]. This study utilizes Aspen Plus to model the hydroxyapatite production process from crab shells while considering both potential advantages and existing challenges. In contrast to solely experimental approaches, this simulation seeks to bridge the scale-up gap by systematically evaluating operating conditions, estimating HAp yield from crab-shell $CaCO_3$ across various processing scenarios, and illuminating consequences for energy requirements and waste minimization. As a result, the findings from this simulation can provide comprehensive insights for sustainable and efficient HAp production, positively influencing both the biomaterials sector and fishing waste management practices.

Aspen Plus is one of the available software programs. Because Aspen Plus can deliver precise findings at each step of the process until the intended product is achieved, it is useful in simulating and optimizing a variety of chemical processes, which lowers the costs needed in the industry's research and development process . In order to gather information on the ratios of raw materials, operating circumstances, and equipment specifications utilized, this study uses Aspen Plus to model the production process of hydroxyapatite from crab shells, taking into account the potential and current issues. Therefore, the outcomes of this simulation can offer thorough information for the sustainable and effective production of HAp, as well as favorably impact the biomaterials sector and fishing waste management.

2. Literature Review

2.1. Blue Crab Shells

Blue crab shells *(Portunus pelagicus)* are one of the types of waste generated from the processing of blue crabs, accounting for 45% of the total blue crabs processed. Based on blue crab catch data, the amount of blue crab shell waste produced reaches 1,236.16 tons per year. This shell waste has not yet been optimized in its processing. In fact, its calcium carbonate content is very high, reaching 53.70-78%. Additionally, the protein and chitin contained in the crab shells reach 15.6-23.9% and 18.7-32.2%, respectively [3][4]. Therefore, to increase the market value of crab shells, the production of chitosan, edible films, and hydroxyapatite (HAp: $Ca_{10}(PO_4)_6(OH)_2$) for medical applications has also been carried out [5][6].

Figure 1. Blue crab shells *(Portunus pelagicus)*

2.2. Hydroxyapatite

Hydroxyapatite (HAp) is a biomaterial frequently used in medical applications for the treatment of orthopedic diseases because it contains calcium phosphate (CaP) similar to the mineral phase of natural bone [17][18]. Adult human bones consist of 60–70% calcium phosphate [19]. Calcium phosphate with a Ca/P ratio of 1.67 is considered ideal for natural bone due to its good biocompatibility [10]. Research on the application of HAp for bone regeneration shows that HAp has several capabilities to support bone tissue during the growth period [11][12]. In addition, HAp has good osteoconductive properties, is non-toxic, non-inflammatory, and has good immunogenicity in both in-vivo and in-vitro tests [13].

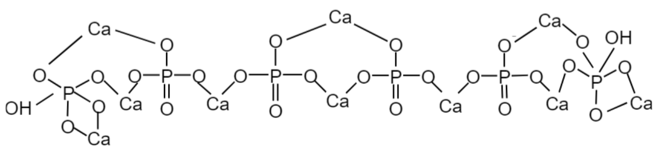

Figure 2. Chemical structure of hydroxyapatite [19]

2.3. Hydroxyapatite Synthesis Method

The production of hydroxyapatite can be carried out using simple and modern methods. Traditionally, methods that can be used in HAp synthesis include precipitation, hydrothermal, and hydrolysis methods. Each of these methods has its own advantages and disadvantages according to its intended use. Generally, what distinguishes the methods is the results of morphological characterization, stoichiometry, and crystallinity [2][20][21]. As technology advances, the synthesis process can also be carried out using microwaves. However, this method has several drawbacks, such as high electricity consumption and the inability to produce on a large scale [22]. Based on the research by Cahyaningrum et al. (2018), the precipitation method is quite promising for use in HAp synthesis because the only byproduct produced is water, there is minimal risk of product contamination, it has a high HAp yield, is inexpensive, and simple [23].

2.4. Process Simulation wit Aspen Plus

Process simulation in the synthesis of hydroxyapatite products has not been widely conducted. However, by simulating the process, predictions regarding the amount of product produced, operating conditions, and the specifications of the equipment required can be studied [24]. Aspen Plus is one of the most effective simulation software for modeling a process because it is supported by several tools commonly used in the chemical industry. Additionally, Aspen Plus has a vast property database, simple models, and is easy to operate. Thus, through this process simulation, costs for research and development in the industry can be reduced [16][25].

Figure 3. Aspen Plus V14

3. Research Method

This research was conducted using the simulation method through Aspen Plus to simulate the production process of hydroxyapatite from crab shell waste. This simulation process involves several main stages, which in detail include:

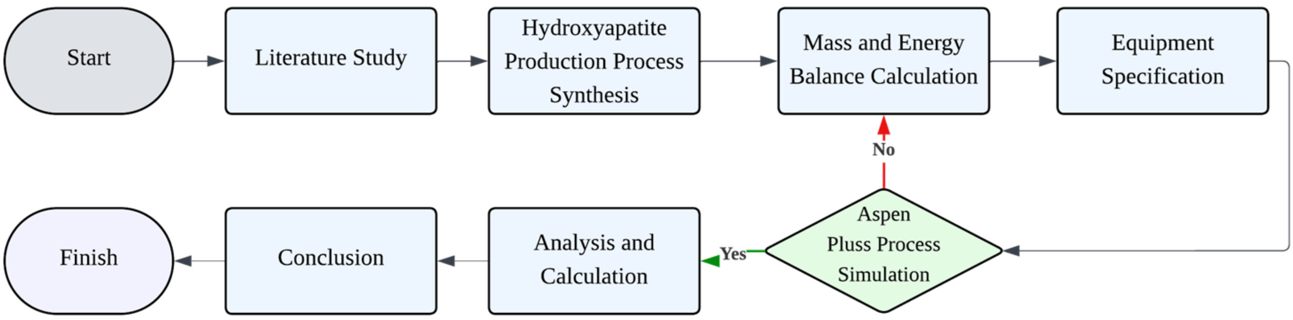

Figure 4. Process flow diagram

3.1. Hydroxyapatite Synthesis Process

3.1.1 Pre-treatment of Crab Shells

The pre-treatment process of the raw material is carried out first by washing the crab shells to remove impurities attached to the shells. The washing process is done using a drum washer with water directly flowing onto the shells. Then, the crab shells are dried using a dryer at a temperature of 105°C to reduce the moisture content in the crab shells. Finally, the size of the crab shells is reduced through crushing and milling processes to facilitate the calcination process.

3.1.2 Calcination and Cooling Process

Calcination is performed on the uniformly sized crab shells, using a furnace at a temperature of 1000°C for 5 hours to decompose calcium carbonate into calcium oxide. Chemical reactions are indicated in reaction (1). To lower the temperature of calcium oxide, the cooling process is carried out using a Grate Cooler. The Grate Cooler will reduce the temperature of CaO from 1000°C to 80°C.

3.1.3 Hydroxyapatite Synthesis Process

The calcium oxide produced from the calcination stage will then be placed into a reactor for the synthesis process. The synthesis process is carried out by reacting calcium oxide with water at a temperature of 80°C and then reacting it with an H_3PO_4 solution. The reaction formed between calcium hydroxide and H_3PO_4 is as follows:

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{2}$$

$$6\ H_3PO_4 + 10\ Ca(OH)_2 \rightarrow Ca_{10}(PO_4)_6\ (OH)_2 + 18H_2O \tag{3}$$

3.1.4 Filtering and Sintering Process

The synthesized hydroxyapatite product is then separated from the water contained within it using a cartridge filter. Thus, the hydroxyapatite can be sintered using a furnace at 800°C for 4 hours. The Sintering process aims to convert the amorphous phase into the crystalline phase in hydroxyapatite. The water content still present in hydroxyapatite will be evaporated during this sintering process.

4. Results and Discussion

4.1. Main Flowsheet

This research utilizes Aspen Plus V14 to simulate hydroxyapatite (HAp) production from blue crab shell waste. The main objective of this simulation is to develop a model capable of replicating the HAp production process based on mass balance, energy balance, determination of operating conditions, and production capacity that have been previously designed. In the simulation, the thermodynamic model employed was the SOLIDS property method. The precipitation phase of hydroxyapatite (HAp) is depicted through a liquid–solid kinetic reactor block, where both stoichiometric reactions and power-law kinetics are defined. Reaction (2) illustrates the hydration process of CaO to form $Ca(OH)_2$, while Reaction (3) details the overall formation of hydroxyapatite from calcium hydroxide and phosphoric acid. The kinetic expressions exhibit an Arrhenius-type dependence on temperature, utilizing a volumetric rate basis (Reac(vol)) and incorporating a liquid–solid reacting phase to reflect the system's heterogeneous characteristics. The flow rates and compositions of all streams provided in Table 1 are based on a design input of 46.48 $kg \cdot h^{-1}$ of CaO introduced into the reactor, derived from the stoichiometric transformation of calcined crab-shell $CaCO_3$ to CaO in the upstream furnace, rather than from throughput data obtained from any existing industrial facility.

Table 1. Mass balance in the reactor unit (first reactor)

Enter		Out	
Component F-210	**Mass**	**Component R-220**	**Mass**
CaO	46.48	Tall	2.32404
H_2O	1691.29	H_2O	1,677.1
		$Ca(OH)_2$	58.3499
Total	**1,737.77**	**Total**	**1,737.77**

Table 2. Energy balance in the first reactor unit

Incoming Energy (kJ)		Outgoing Energy (kJ)	
Δ	1,525.104	ΔWood	7661,815
Q Supply	9,916.393	ΔHrx	3283,862
		Q loss	495,819
	11,441.4977		**11,441.4977**

Table 3. Mass balance in the reactor unit (second reaction)

Enter		Out	
Component	**Mass**	**Component**	**Mass**
		Heading to L-227	
$Ca(OH)_2$	58.3	$Ca(OH)_2$	2.9
H_3PO_4	111.4	H_3PO_4	67.4
N_2	237.04	N_2	237.04
H_2O	2,243.9	$Ca_{10}(PO_4)_6(OH)_2$	75.2
	2,650.67	H_2O	2,268.1
			2,650.67
Total	**2,650.67**	**Total**	**2,650.67**

Table 4. Energy balance in the second reactor unit

Incoming Energy (kJ)		Outgoing Energy (kJ)	
Δ	39,199.183	ΔWood	442,131.626
Q Supply	423,388.942	ΔHrx	-712.947
		Q loss	21,169.447
	462,588.125		**462,588.125**

Table 5. Operating conditions

Tool	Temperature Inlet (°C)	Temperature Outlet (°C)	Pressure (atm)
Furnace (Q-150)	60	1,000	1
Grate Cooler (E-160)	1,000	80	1
Silo (F-210)	80	80	1
First Reactor (R-220A)	80	50	1
Second Reactor (R-220A)	800	60	1
Grate Cooler (E-250)	60	60	1
Silo (F-310)	60	50	1

Determining the components, thermodynamic models, main flowsheet design, operating condition data on streams and blocks, and starting the simulation are the first steps in the process.

4.2. Determination of Components

In the properties section, component determination is done at the start of the simulation. Each component that will be used in the simulation process must be entered. Table 6 lists the materials needed to simulate the process of making hydroxyapatite from crab shells.

Table 6. Elements of the simulation of the hydroxyapatite production process

Component ID	***Type***	***Alias***	***CAS Number***
CALCI-01	*Solid*	$CaCO_3$	471-34-1
ORTHO-01	*Conventional*	H_3PO_4	7664-38-2
WATER	*Conventional*	H_2O	7732-18-5
NITRO-01	*Conventional*	N_2	7727-37-9
OXYGEN-01	*Conventional*	O_2	7782-44-7
CALCI-02	*Solid*	CaO	1305-78-8
CALCI-03	*Solid*	$Ca(OH)_2$	1305-62-0
CA10(-01	*Solid*	$Ca_{10}P_6O_{26}H_2$	
CARBO-01	*Conventional*	CO_2	124-38-9
POLY-01	*Conventional*	$C_6H_{10}O_2$-N_{39}	24980-41-4
ACETI-01	*Conventional*	$C_2H_4O_2$	64-19-7

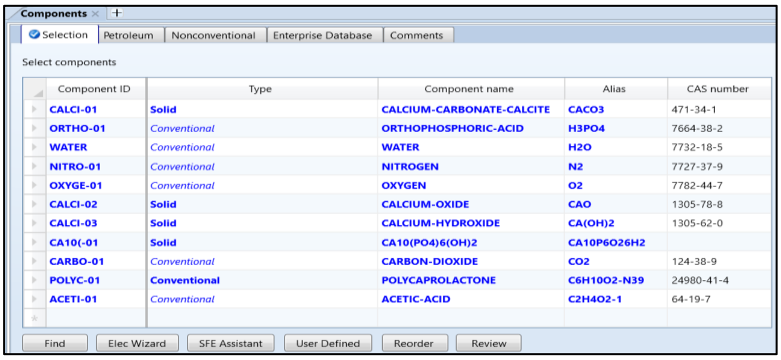

Figure 5. Component Selection with Aspen Plus

4.3. Determination of Model

Choosing the model type for the simulation is the next step after choosing every component. Depending on the circumstances of the process to be mimicked, the model type is chosen. The techniques section offers a variety of approaches. The SOLIDS method was used for the simulation of the hydroxyapatite synthesis process from crab shells, as illustrated in Figure 6. The SOLIDS method was chosen as the global property approach because the flowsheet primarily consists of non-volatile inorganic solids ($CaCO_3$, CaO, $Ca(OH)_2$, and $Ca_{10}(PO_4)_6(OH)_2$) along with liquid water. The main aim is to achieve reliable estimates of enthalpy and density for solid phases while ensuring comprehensive mass and energy balances, rather than rigorously modeling multicomponent vapor-liquid equilibrium. Within Aspen Plus, the SOLIDS method treats pure solids as incompressible phases characterized by temperature-dependent heat capacities and heats of formation. This treatment is suitable when solid–solid and solid–liquid transformations are represented through stoichiometric reactors and separators, especially when gas-liquid non-ideality is not a significant concern in design [26].

However, selecting this method comes with certain constraints. The SOLIDS framework does not provide explicit modeling for electrolyte speciation, pH-dependent calcium phosphate solubility, or ion activity coefficients in the aqueous phase. Consequently, it cannot accurately predict detailed liquid-phase equilibria. A more thorough analysis of these factors would necessitate an electrolyte thermodynamic framework like ELECNRTL or ENRTL-RK, which has been commonly applied in process simulations involving reactive aqueous systems and those containing CO_2 [27]. In contrast, cubic equations of state such as Peng-Robinson and activity-coefficient models like NRTL are generally preferred for non-electrolyte gas-liquid systems, where vapor-liquid equilibrium and non-ideal liquid behavior significantly affect design and optimization [28].

For the current synthesis of hydroxyapatite from crab shells, operating pressures are near ambient levels, vapor fractions are minimal, and key performance metrics focus on solid yield, overall conversion rates, and energy requirements. Therefore, employing Peng-Robinson or NRTL would complicate the model without offering proportional improvements in accuracy concerning the quantities that matter most [28]. As a result, the SOLIDS method is deemed a suitable preliminary option for depicting the thermophysical properties of this system.

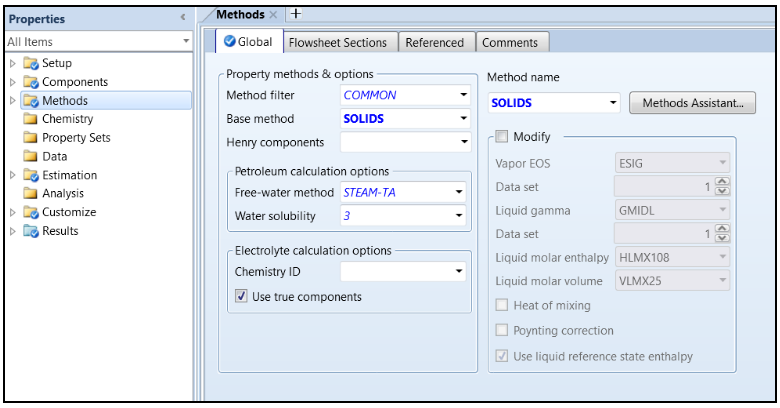

Figure 6. Determination of Methods in Simulation of Hydroxyapatite Production Process

4.4. Process Sequence

Developing the primary flowsheet, as seen in Figure 7, is the most crucial step in simulating the synthesis of hydroxyapatite using Aspen Plus V14. When choosing the kinds of equipment to employ, the process description is essential. The total number of components in a flow, equipment specifications, and operational status data must also be included. The mass and energy balance data that were previously computed are used to change the operational condition data and the total number of flows in each stream in this process simulation. Figures 8 and 9 show examples of the data input procedure for each flow, operational circumstances, and equipment specifications.

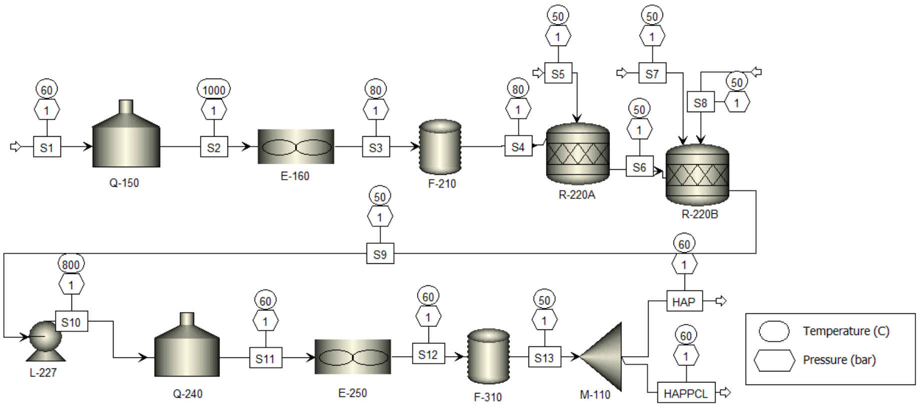

Figure 7. Main Flowsheet Hydroxyapatite Production Process

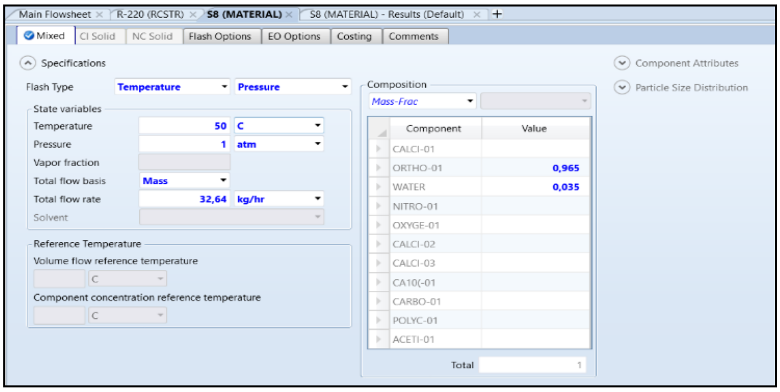

Figure 8. Input of total component data on each stream

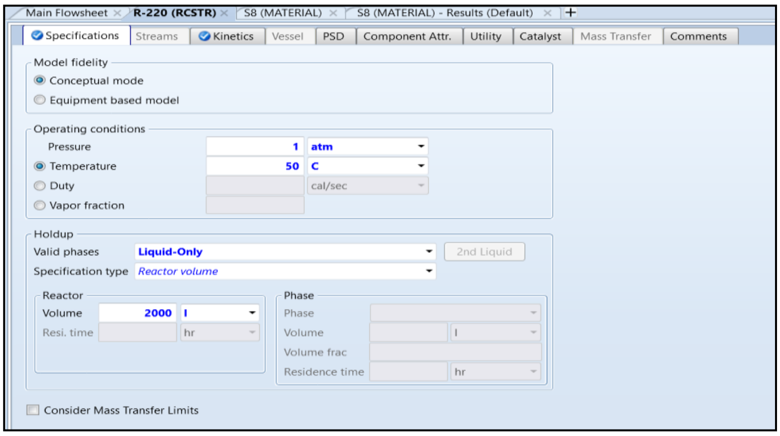

Figure 9. Data Input, Operating Conditions, and Equipment Specifications

4.5. Simulation Results

The simulation of the hydroxyapatite production process using Aspen Plus V14 can be run after all data on streams and blocks have been filled in. Based on the incoming streams and the specifications of the equipment determined previously, the product data generated is as shown in Figure 10. The simulation results indicate that the hydroxyapatite product that can be produced from 46.48 kg/h of calcium oxide is 150.246 kg/h. The application of Aspen Plus in systems involving Ca–P–H_2O aligns with recent research that has modeled and validated phosphorus recovery and calcium-phosphate processes against experimental findings. These studies have shown a strong correlation concerning mass and energy balances as well as product yields. Furthermore, Aspen Plus has effectively been utilized to forecast the behavior of calcium and phosphate ions, along with the solubility of calcium phosphate in water, by employing suitable thermodynamic packages for electrolytes. This further reinforces its appropriateness for simulating calcium phosphate systems [29][30]. The hydroxyapatite previously underwent a calcination process in the furnace (Q-150) to decompose calcium carbonate into calcium oxide. Then, the calcium oxide is cooled from a temperature of 1000°C to 80°C using a grate cooler (E-160). After that, calcium oxide is stored in the silo tank (F-210) before being fed into the reactor (R-220).

	Units	S6	S9	HAP
Description				
From		R-220A	R-220B	M-110
To		R-220B	L-227	
Stream Class		CONVEN	CONVEN	CONVEN
Maximum Relative Error				
Cost Flow	$/hr			
− MIXED Substream				
Phase				
Temperature	C	50	50	60
Pressure	bar	1	1	1.01325
Molar Vapor Fraction		0	0	0
Molar Liquid Fraction		0.912085	0.977057	0.977057
Molar Solid Fraction		0.0879149	0.022943	0.022943
Mass Vapor Fraction		0	0	0
Mass Liquid Fraction		0.718594	0.56782	0.56782
Mass Solid Fraction		0.281406	0.43218	0.43218
Molar Enthalpy	cal/mol	-82142.3	-109555	-109353
Mass Enthalpy	cal/gm	-3592.31	-3513.83	-3507.38
Molar Entropy	cal/mol-K	-40.0486	-44.8041	-44.1918
Mass Entropy	cal/gm-K	-1.75144	-1.43704	-1.4174
Molar Density	mol/cc	0.05128	0.0539168	0.0536575
Mass Density	gm/cc	1.17258	1.68102	1.67294
Enthalpy Flow	cal/sec	-215120	-357747	-355662
Average MW		22.8661	31.1781	31.1781
− Mass Flows	**kg/hr**	**215.58**	**366.52**	**365.054**
CALCI-01	kg/hr	0	0	0
ORTHO-01	kg/hr	0	1.46354	1.45768
WATER	kg/hr	154.915	206.654	205.827
NITRO-01	kg/hr	0	0	0
OXYGE-01	kg/hr	0	0	0
CALCI-02	kg/hr	2.324	2.324	2.3147
CALCI-03	kg/hr	58.3414	5.83207	5.80874
CA10(-01	kg/hr	0	150.246	149.645

Figure 10. Hydroxyapatite Production Process Simulation Results

For an economic analysis of the hydroxyapatite manufacturing process, we applied the Aspen Process Economic Analyzer (APEA) linked to the Aspen Plus V14. An initial set of major assumptions has been developed using the APEA database as basis crab shell waste was a zero-cost feedstock, that raw materials costs are largely related downstream to secondary reagents, electricity, cooling water, and fuel prices were taken from the widely used Aspen economic database, the plant would keep running at a fixed frequency for 8,000 hours a year and a target return rate of 20% was forecast, with a projected lifetime of 20 years of equipment.

Enabled by **Aspen Process Economic Analyzer (APEA)**

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Summary | Utilities | Unit operation | Equipment | TEMA HEX | Quoted equipment | Agitated reactor | Centrif pump

Total Capital Cost [USD]	1,937,260
Total Operating Cost [USD/Year]	1,305,280
Total Raw Materials Cost [USD/Year]	0
Total Product Sales [USD/Year]	0
Total Utilities Cost [USD/Year]	43,277.3
Desired Rate of Return [Percent/'Year]	20
P.O. Period [Year]	0
Equipment Cost [USD]	89,700
Total Installed Cost [USD]	473,400

Figure 11. Economic Analysis Results with Aspen Process Economic Analyzer

Based on the above considerations, and considering that the volume of CaO needed in the reactor entry of 46.48 $kg \cdot h^{-1}$, APEA projects the total installed equipment cost of the reactor, which will ultimately amount to USD 473,400, while the total equipment cost is USD 89,700 to purchase. The total capital cost of the facility is projected to be USD 1,937,260, with average annual operating costs of USD 1,305,280 and utilities at approximately USD 43,277. Due to the absence of determining raw material prices as well as product selling prices in this baseline calculation, raw material costs and product sales are considered zero. Therefore, this analysis should be considered as an initial assessment of the capital intensity and utility needs, not as an exhaustive profitability assessment. The results indicate that this procedure fits a medium capital-intensity classification under the present cost assumptions but has large sensitivity to operational costs, particularly utilities, and provides a quantitative basis for future optimization in operating conditions, scale adjustments, and integration with waste management regimes.

In the reactor section, water and phosphoric acid will be added, and the reaction that occurs is as follows:

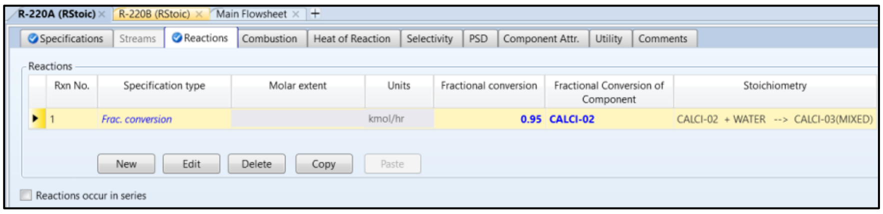

Figure 12. Reaction to the First Reactor

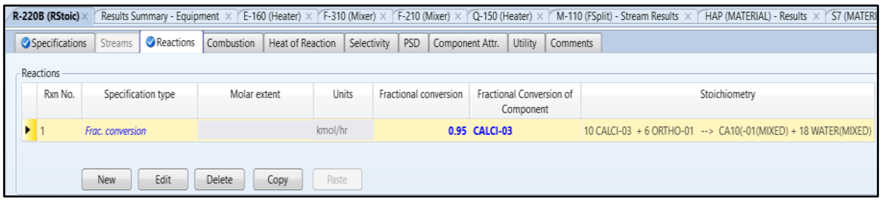

Figure 13. Reaction at the Second Reactor

The hydroxyapatite product is then sintered using a furnace (Q-240) at a temperature of 800°C to convert the amorphous phase of hydroxyapatite into the crystalline phase. After the sintering process is complete, the hydroxyapatite is cooled using a grate cooler (E-250) until its temperature reaches 60°C. Then, the hydroxyapatite is ball-milled to reduce its size. The hydroxyapatite product produced at a rate of 149.645 kg/hr will be packed as a hydroxyapatite product. The separation is carried out using a splitter (M-110).

5. Conclusion

The potential of crab shell waste in Indonesia reaches 1,236.16 tons per year, providing significant opportunities for its processing into hydroxyapatite (HAp) products. This process not only reduces environmental pollution but also increases the added value of the product and reduces dependence on imported hydroxyapatite. Based on the production process simulation, using 46.48 kg/hour of calcium oxide, 150.246 kg/hour of HAp is produced through the precipitation method using phosphoric acid (H_3PO_4) precursor. The annual production projection shows the potential to produce HAp reaching 1,451.81 tons/year. Therefore, the optimization of processing crab shell waste into hydroxyapatite is highly recommended in Indonesia for better economic and environmental benefits. Nevertheless, this study encounters several limitations. The existing Aspen Plus model has not been validated against pilot-scale experimental data specific to Indonesian crab-shell streams. Additionally, the evaluation is confined to process simulation and does not encompass a comprehensive cradle-to-gate life-cycle assessment (LCA) or detailed techno-economic optimization. Therefore, future research should aim to incorporate experimental validation, LCA, and multi-objective process optimization to enhance the design of hydroxyapatite (HAp) production from crab shell waste and effectively align it within circular bioeconomy strategies.

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