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Design of Batch Reactor for the Production of $SnCl_2$ Particles

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Abstract

Purpose: This study aims to design and evaluate a batch reactor for industrial-scale production of Stannous Chloride ($SnCl_2$) from Indonesian tin resources, supporting downstream processing of tin into higher-value chemical products.

Methodology: A computational design approach was applied using sequential chemical engineering equations in Microsoft Excel. The process is based on the reaction between Tin (Sn) and Hydrochloric Acid (HCl). The reactor is designed as a cylindrical batch vessel with a dished top and conical bottom, made of stainless-steel SA 240 Grade 316. Operating conditions include 80°C, 1 atm, and 1-hour batch time, with 1,000 kg/h tin feed and 95% conversion. Mass balance, sizing, and mechanical design calculations were performed, including stirrer specifications.

Results: The reactor has a volume of 29.0184 ft^3, diameter of 2.7889 ft, and height of 5.6690 ft. Mass balance yields 1,517.31 kg/h $SnCl_2$ and 16.13 kg/h H_2. The system uses a 2 Hp axial turbine stirrer with 16.7334 in impeller diameter.

Conclusions: The designed reactor demonstrates technical feasibility for industrial $SnCl_2$ production and complies with ASME pressure vessel standards.

Limitations: The model does not include effectiveness factors for diffusion limitations in heterogeneous reactions.

Contributions: This study provides a validated engineering design reference for $SnCl_2$ production and supports downstream tin industry development in Indonesia

Keywords: *Batch Reactor Design, Mass Balance, $SnCl_2$ Production, Stannous Chloride, Stirrer Configuration*

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1. Introduction

Indonesia's tin industry occupies a globally significant position. The country holds the world's second-largest tin reserves after China, with confirmed reserves distributed primarily across the Bangka-Belitung archipelago and the Riau Islands (Agus, Wulandari, Primananda, Hendryan, & Harianja, 2017; Rahmawati, Martini, Purnomo, & Nasikin, 2022). National tin production reached 33,444 metric tonnes in 2018, representing a 10.6% year-on-year increase and reflecting sustained growth in upstream production capacity (Agus et al., 2017). Despite this upstream strength, the Indonesian tin industry has historically concentrated economic activity in ore extraction, smelting, and ingot export rather than in the downstream chemical and materials processing sectors that generate substantially higher value per unit of tin. The gap between Indonesia's upstream production volume and its downstream processing capacity represents a significant economic opportunity that has attracted increasing policy attention from the Indonesian government in recent years (Tajuddin, Amal, Widayatno, Wulandari, Purnomo, & Nasikin, 2021; Sudarmadi, Yusuf, & Hariadi, 2023).

Approximately 16% of total global tin ingot production is processed into tin-derived chemical compounds. These compounds serve critical industrial functions across a wide range of manufacturing sectors: $SnCl_2$ and other tin salts are used in electroplating baths, where they constitute 47% of solder applications; tin plate manufacturing relies on tin coatings deposited from $SnCl_2$ electrolytes; tin compounds function as stabilizers in Polyvinyl Chloride (PVC) processing; and tin-based catalysts participate in organic synthesis reactions for pharmaceuticals and specialty chemicals (Evans, 1998; Díez, Sastre, & Coca, 1989). The upstream-downstream gap means that Indonesia currently exports a large fraction of its tin production in low-value ingot form, forgoing the processing margin available through chemical conversion.

Stannous Chloride ($SnCl_2$), also known as tin (II) chloride, is among the most economically important tin derivative compounds. Its applications span electroplating as a source of Sn^{2+} ions in acid tin plating baths, reduction of noble metal salts in sensitization processes for electroless plating, catalysis in esterification and transesterification reactions, and stabilization of PVC against thermal degradation (Ahmed, Fjellvag, & Kjekshus, 1998; Alves-Rosa, Vasconcellos, Vieira, Santilli, & Pulcinelli, 2019; Dabbawala, Mishra, & Hwang, 2013; Nandiyanto, Maulana, Oktiani, & Ragadhita, 2022). The industrial production route from tin metal and hydrochloric acid is well established, proceeding through the dissolution of tin in aqueous HCl to form liquid $SnCl_2$ solution, followed by evaporation and crystallization to yield solid $SnCl_2$ product (Tajuddin et al., 2021). Tajuddin et al. (2021) confirmed through systematic optimization that $SnCl_2$ yield is maximized at higher HCl concentrations, higher reaction temperatures, and finer tin powder particle sizes, with the best results at 500 mesh particle size.

A batch reactor is the most appropriate vessel configuration for $SnCl_2$ production at industrial scale. Batch reactors contain the reactive substances for a defined operating period, allowing complete reaction, mixing, and product formation within a single vessel cycle before discharge (Saputro, 2021; Levenspiel, 2023). Compared to continuous flow reactors, batch reactors offer advantages including constructional simplicity, operational flexibility for small to medium production volumes, adaptability to changing product specifications, and suitability for reactions requiring high conversion within a fixed time period (Roy, & Aditya, 2015; Fogler, 2020). These advantages are particularly relevant for $SnCl_2$ production at early stages of downstream industry development, where production volumes may not justify the capital investment of continuous processing equipment and where product specification flexibility is commercially important.

The engineering design of batch reactors for chemical production applications has been addressed by a substantial body of literature across diverse product categories. Talaghat, Mokhtari, and Saadat (2020) optimized a batch reactor for biodiesel synthesis from microalgae, demonstrating that computational design can significantly improve conversion efficiency. Fernandez, Gamallo, Gonzalez-Gomez, Vazquez-Vazquez, Rivas, Pintado, and Moreira (2019) designed a magnetic sequential batch reactor for antibiotics removal using Fe_3O_4/ZnO nanocomposites, highlighting the role of reactor geometry in enhancing mass transfer. Otadi and Monajjemi (2021) synthesized Mn-doped ZnO nanoparticles in a batch system using Taguchi experimental design, achieving systematic optimization of reaction parameters. Sodha, Tipre, and Dave (2020) optimized a biohydrometallurgical batch reactor for copper extraction from waste printed circuit boards, documenting the importance of stirrer design for solid-liquid contact. Merzari, Lucian, Volpe, Andreottola, and Fiori (2018) designed a bench-scale batch reactor for hydrothermal carbonization of biomass, establishing thermal management principles transferable to exothermic liquid-solid systems. Luo and Crittenden (2019) demonstrated systematic approaches to scaling nanomaterial adsorbent synthesis from bench to engineering scale in batch configurations.

In the Indonesian context specifically, reactor design studies have addressed sugar industry liquefaction reactors (Saputro, 2021), wastewater treatment applications by Hidayat, Pertiwi, and Syahputra (2021), and biofuel processing. However, no published study has specifically designed a batch reactor for industrial-scale $SnCl_2$ production from Indonesian tin resources. This study addresses this gap through a complete computational design encompassing vessel dimension, structural specifications derived from ASME pressure vessel standards, stirrer parameters, and mass balance verification. The design provides engineering parameters directly applicable to downstream tin industry development, supporting Indonesia's strategic objective of increasing the domestic value added from its mineral resources (Agus et al., 2017; Tajuddin et al., 2021; Rahmawati et al., 2022).

The research objectives are threefold. The first objective is to determine the mass balance for $SnCl_2$ production at a 1,000 kg/h Sn feed basis with 95% conversion, establishing the material flows that govern reactor sizing. The second objective is to compute the reactor vessel dimensions, wall thicknesses, and lid specifications consistent with ASME pressure vessel design codes for the specified operating conditions. The third objective is to determine the stirrer configuration, impeller dimensions, power requirement, shaft diameter, and shaft length for effective mixing during the dissolution phase of the production process. Together, these objectives constitute a complete batch reactor design ready for engineering evaluation and scale-up to an industrial facility.

2. Literature Review

2.1 Stannous Chloride: Chemistry, Properties, and Industrial Applications

Stannous chloride is a white crystalline solid with molecular formula $SnCl_2$ and molecular weight 189.60 g/mol. It exists in both anhydrous form ($SnCl_2$) and as the dihydrate ($SnCl_2 \cdot 2H_2O$), with the anhydrous form melting at 247°C and both forms soluble in concentrated HCl, ethanol, and acetone (Ahmed, Fjellvag, & Kjekshus, 1998; Nandiyanto, Maulana, Oktiani, & Ragadhita, 2022). The compound exhibits strong reducing properties, readily oxidizing to tin (IV) chloride ($SnCl_4$) in the presence of air, which makes storage under inert conditions or in acid solution important for industrial applications (Tajuddin, Amal, Widayatno, Wulandari, Purnomo, & Nasikin, 2021; Prasetyo, Nugroho, & Wahyudi, 2022).

The primary industrial applications of $SnCl_2$ exploit its reducing and coordinating chemistry. In electroplating, $SnCl_2$ dissolves as the source of Sn^{2+} ions in acid tin plating baths, where it is co-deposited to form protective tin coatings and solder alloys on copper, steel, and other substrate materials (Díez, Sastre, & Coca, 1989; Evans, 1998). The electroplating industry accounts for approximately 47% of global tin chemical consumption, making it the dominant market for tin derivatives including $SnCl_2$. In the sensitization step of electroless plating, $SnCl_2$ is used to reduce palladium or other noble metal salts onto substrate surfaces, creating catalytic nuclei for subsequent autocatalytic metal deposition (Alves-Rosa, Vasconcellos, Vieira, Santilli, & Pulcinelli, 2019; Wulandari, Wismogroho, Widayatno, Amal, & Kusuma, 2021). As a PVC thermal stabilizer, tin compounds including $SnCl_2$ derivatives react with HCl released during degradation to interrupt the autocatalytic dehydrochlorination chain reaction that causes discoloration and embrittlement (Dabbawala, Mishra, & Hwang, 2013). In organic chemistry, $SnCl_2$ serves as a mild and selective reducing agent for nitro groups, aldehydes, and other functional groups without the safety hazards associated with stronger reductants (Ahmed et al., 1998; Yusnitasari, Setiyadi, & Kurniawan, 2022).

The production of $SnCl_2$ from tin metal and HCl is the dominant industrial synthesis route. The reaction is heterogeneous, involving solid Sn particles dissolving in aqueous HCl solution. Tajuddin et al. (2021) systematically investigated the influence of particle size, HCl concentration, and temperature on $SnCl_2$ yield, concluding that 500 mesh tin powder provides significantly higher surface area and therefore higher reaction rates than coarser particles. Tajuddin et al. (2021) synthesized $SnCl_2$ from tin powder waste generated in the powderization process, demonstrating that industrial waste streams can serve as the tin feedstock, which is relevant to integrated tin processing operations. Taslimah, Ismail, and Sumardjo (2003) demonstrated the synthesis of $SnCl_2$ from tin-coated packaging waste, establishing the broader applicability of the Sn-HCl reaction to secondary tin sources. These synthesis studies collectively confirm the robustness of the Sn-HCl route under varying feedstock and process conditions, supporting its selection as the production chemistry for the present reactor design.

2.2 Batch Reactor Design Principles

A batch reactor is a closed vessel in which reactants are charged, reaction proceeds for a defined time under controlled conditions of temperature, pressure, and mixing, and the product mixture is then discharged. The defining characteristic of batch operation is the time-dependent nature of conversion: because no material enters or leaves during the reaction period, conversion increases monotonically with time until the batch is terminated (Levenspiel, 2023; Fogler, 2020). For the Sn-HCl system, the reaction is irreversible and proceeds until either Sn is fully dissolved or the batch time is reached, making the 95% conversion target achievable within the 1-hour design batch time based on the kinetics reported by Tajuddin, Amal, Widayatno, Wulandari, Purnomo, and Nasikin (2021).

The design of a batch reactor vessel follows established chemical engineering principles and pressure vessel codes. Vessel sizing is governed by the required liquid volume, which is determined by the volumetric flow rate of reactants and the batch time, with a design factor applied to account for headspace, foam, and splashing. The standard design factor for industrial batch reactors is 80% liquid fill, meaning the total vessel volume is 1.25 times the liquid volume (Walas, 1990; Towler, & Sinnott, 2022). Vessel wall thickness is calculated from the design pressure, vessel diameter, material allowable stress, and weld efficiency according to ASME Boiler and Pressure Vessel Code Section VIII Division 1. The design pressure is typically set equal to the maximum operating pressure plus a safety margin, accounting for the hydrostatic head of the liquid contents (Towler & Sinnott, 2022).

Material selection for corrosive service such as HCl handling requires careful consideration of corrosion resistance. Stainless steel SA 240 Grade M Type 316 is an austenitic chromium-nickel-molybdenum stainless steel with superior resistance to chloride-containing environments compared to standard 304 grade, due to the addition of 2-3% molybdenum which reduces pitting and crevice corrosion in acidic chloride media (Bhadeshia, & Honeycombe, 2017; Nandiyanto, Ragadhita, & Fiandini, 2023). The selection of this grade for both the reactor vessel and the stirrer components is consistent with best practice for HCl service in chemical process equipment.

Stirrer design for solid-liquid systems such as the Sn powder-HCl system is primarily governed by the requirement to maintain solid particles in suspension and to provide adequate liquid-phase mixing for mass transfer from the dissolved Sn^{2+} species to the bulk. Axial flow impellers, including axial turbines with pitched blades, are preferred for solid suspension applications because they generate the downward axial flow that prevents particle settling while also creating radial circulation that ensures uniform concentration throughout the vessel (Paul, Atiemo-Obeng, & Kresta, 2004; Nienow, Harnby, & Edwards, 2022). The 4-blade 45° axial turbine selected for this design is a standard configuration for solid-liquid mixing in process vessels, widely used in mineral processing, crystallization, and dissolution applications (Paul et al., 2004; Zulkifli, Pratama, & Bintoro, 2021).

2.3 Previous Batch Reactor Design Studies in Comparable Applications

A review of recent batch reactor design studies reveals consistent application of computational approaches across diverse chemical production contexts. Talaghat et al. (2020) employed a computational model to design and optimize a batch reactor for biodiesel production from microalgae, accounting for the transesterification reaction kinetics and thermal effects to determine optimal vessel dimensions and operating conditions. Their work demonstrated the effectiveness of sequential equation-based design for preliminary reactor sizing prior to experimental validation. Fernandez et al. (2019) developed a novel magnetic sequential batch reactor for photocatalytic degradation of antibiotics, where the reactor geometry was specifically optimized for the light penetration and mass transfer requirements of the photocatalytic process, illustrating how vessel design must be adapted to the specific mass and energy transfer requirements of the reaction system.

Otadi et al. (2021) synthesized Mn-doped ZnO nanoparticles in a batch system using Taguchi experimental design to systematically optimize reagent concentrations, temperature, and reaction time within a computationally designed vessel, demonstrating the integration of statistical design of experiments with process engineering design. Sodha et al. (2020) optimized a biohydrometallurgical batch reactor for copper extraction from waste printed circuit boards, documenting that impeller type, speed, and diameter significantly affect solid suspension quality and therefore leaching efficiency, a finding directly relevant to the Sn powder dissolution system addressed in the present study. Merzari et al. (2018) designed a bench-scale batch reactor for hydrothermal carbonization of biomass, with particular attention to the exothermic heat of reaction and the associated thermal management requirements, an issue also relevant to the exothermic Sn-HCl dissolution reaction.

In the Indonesian chemical engineering education and research context, batch reactor design studies have been applied to sugar industry liquefaction (Saputro, 2021) and pharmaceutical synthesis (Hidayat, Pertiwi, & Syahputra, 2021). Saputro (2021) performed both technical and economic analysis of a liquefaction reactor for the sugar industry, demonstrating the methodology of combining design equations with economic feasibility assessment that future work on the $SnCl_2$ batch reactor should incorporate. The broader literature confirms that computational batch reactor design, validated through mass balance and dimensional analysis, is a well-established and accepted methodology for preliminary process engineering assessment, providing the foundation for the approach adopted in this study (Fogler, 2020; Towler & Sinnott, 2022; Levenspiel, 2023).

3. Research Methodology

3.1 Synthesis Chemistry of $SnCl_2$

$$Sn(s) + 2HCl(aq) \rightarrow SnCl_2(l) + H_2(g) \tag{1}$$

Stannous chloride is produced through the reaction of tin metal (Sn) with hydrochloric acid (HCl), following the process established by Tajuddin et al. (2021). HCl was selected as the chloride ion source based on its documented superiority over alternative chloride sources in achieving complete tin dissolution at practical reaction temperatures (Ahmed et al., 1998; Taslimah et al., 2003). The production proceeds through two sequential reactions. The first reaction is the dissolution of tin metal in aqueous hydrochloric acid to yield liquid stannous chloride and hydrogen gas as can be seen in Formula 1

$$SnCl_2(l) + heat \rightarrow SnCl_2(cr) \tag{2}$$

This reaction is heterogeneous, proceeding at the surface of solid tin particles in contact with aqueous HCl. The second reaction is the evaporation and crystallization of the liquid $SnCl_2$ solution upon heating to yield crystalline $SnCl_2$ product of Formula 2

The synthesis basis for all mass balance and reactor sizing calculations in this study is 1,000 kg/h tin feed with 95% Sn conversion. The molecular weights used throughout the calculations are: Sn = 118.71 g/mol, HCl = 36.46 g/mol, $SnCl_2$ = 189.60 g/mol, and H_2 = 2.016 g/mol. The HCl input is calculated stoichiometrically as 2 mol HCl per mol Sn, giving a molar HCl requirement equal to twice the molar Sn feed.

3.2 Reactor and Stirrer Design Specifications

Table 1. Design assumptions and specifications for the $SnCl_2$ batch reactor and stirrer

Specification	Value
Reactor type	Upright cylinder; dished standard top cover; conical bottom cover, apex angle 120°
Stirrer type	Axial turbine, 4 blades, angle 45°
Stirrer impeller material	High Alloy Steel SA 240 Grade M Type 316

Specification	Value
Stirrer shaft material	Hot Roller Steel SAE 1020
Operating temperature	80°C
Operating pressure	1 atm
Operation time	1 hour
Construction material (vessel)	Stainless Steel SA 240 Grade M Type 316
Allowable stress (f)	18,750 psi
Weld joint type	Double welded butt joint (E = 0.8)
Corrosion allowance (C)	0.0625 in
Total incoming substance	3,558.8563 lb/h
Volumetric rate	23.2147 ft^3/h
Sn conversion	95%

Table 1 show the design assumptions and material specifications for the batch reactor and stirrer. These specifications reflect standard chemical engineering design practice for corrosive service at near-atmospheric operating pressure (Towler & Sinnott, 2022; Bhadeshia & Honeycombe, 2017). The reactor is fabricated from stainless steel SA 240 Grade M Type 316, selected for its corrosion resistance in the acidic HCl reaction environment. The stirrer impeller uses the same austenitic stainless steel grade, while the shaft uses Hot Roller Steel SAE 1020 for its torsional strength properties. The double welded butt joint with weld efficiency E = 0.8 is standard for pressure vessels in this operating pressure range according to ASME Section VIII Division 1. The corrosion allowance of 0.0625 in (1.59 mm) is appropriate for the anticipated service life in dilute acid service.

3.3 Mathematical Model and Design Equations

The complete batch reactor and stirrer design is computed through sequential application of 18 engineering equations. Table 2 presents each equation, the parameter it computes, the relevant variables, and the equation number referenced in the calculations. All computations were performed in Microsoft Excel to ensure reproducibility and to allow systematic sensitivity analysis of input parameters (Towler & Sinnott, 2022; Fogler, 2020).

The reactor total volume (Vr) is determined from the liquid volume in the cylinder (Vlc) with the 80% liquid fill factor applied as Vr = Vlc / 0.8, ensuring adequate headspace for the Sn-HCl reaction. The vessel diameter is derived by simultaneously solving the cylindrical volume equation with the design constraint that cylinder height Hc equals 1.5 times the inner diameter di, which is the standard proportioning for batch reactor vessels to provide adequate mixing at moderate aspect ratios (Paul, Atiemo-Obeng, & Kresta, 2004). The cylinder wall thickness tc is computed from the ASME thin-wall pressure vessel formula: tc = (Pi x di) / (2fE - 1.2Pi) + C, where Pi is the design pressure in psig, f is the material allowable stress, E is the weld joint efficiency, and C is the corrosion allowance. This formula is the standard ASME Section VIII Division 1 expression for cylindrical shell thickness under internal pressure.

The design pressure Pi combines the hydrostatic head pressure of the liquid contents (computed from fluid density, gravitational acceleration, and liquid height) with the vapor pressure contribution at operating temperature. The top lid thickness (tht) is computed using the ASME standard dished head formula: tht = (Pi x di) / (2fE - 0.2Pi) + C, which applies to standard ellipsoidal or dished heads. The conical bottom lid thickness (thb) applies the conical section formula: thb = (Pi x di) / (2fE cos(α) - 1.2Pi) + C, where α is the half apex angle of the cone (60° for a 120° full apex angle). The total reactor height Hr sums the cylinder height, the top and bottom lid heights, and a safety clearance factor.

Table 2. Reactor and stirrer design equations with variable definitions

Eq.	Parameter	Symbol and Unit	Equation and Key Variables
1	Total reactor volume	Vr (ft^3)	Vr = Vlc / 0.8; Vlc = liquid volume in cylinder from volumetric rate x operation time
2	Vessel inner diameter	di (ft)	Derived from Vr with Hc = 1.5di and conical bottom apex angle 120°
3	Liquid volume in cylinder	Vlc (ft^3)	Vlc = Volumetric rate x Operation time
4	Liquid height in cylinder	Hlc (ft)	$Hlc = Vlc / (\pi/4 \times di^2)$
5	Design pressure	Pi (psig)	$Pi = \rho \times g \times Hlc$ + vapor pressure at 80°C; ρ = fluid density
6	Cylinder thickness	tc (in)	tc = (Pi x di) / (2fE - 1.2Pi) + C; f = 18,750 psi; E = 0.8; C = 0.0625 in
7	Cylinder height	Hc (ft)	Hc = 1.5 x di
8	Top lid thickness and height	tht (in), ht (in)	tht = (Pi x di) / (2fE - 0.2Pi) + C; ht from standard ASME dished head geometry
9	Bottom lid thickness and height	thb (in), hb (in)	thb = (Pi x di) / (2fE cosα - 1.2Pi) + C; α = 60° (half apex angle); hb from conical geometry
10	Total reactor height	Hr (ft)	Hr = Hc + ht + hb + Sf; Sf = safety clearance factor (2.5 in)
11	Impeller diameter	Da (ft)	Da = Dt / 3; Dt = inner vessel diameter di
12	Impeller clearance from bottom	Zi (ft)	Zi = Dt / 4
13	Impeller blade length	l (ft)	l = Da / 4
14	Impeller blade width	W (ft)	W = Da / 5
15	Number of stirrers	n (integer)	n = Hlc / (2.5 x Da); rounded up to next integer
16	Stirring power required	H (Hp)	$P = \varphi \times \rho \times N^3 \times Da^5 / gc$; φ = 0.9; N = 100 rpm; H = P / (1 - 0.1 - 0.15)
17	Shaft diameter	D (in)	$D = (16T / \pi S)^{(1/3)}$; T = torsion moment from H; S = maximum shearing stress of shaft material
18	Shaft length	L (ft)	L = Hc + ht - Zi - l

Table 2 show this table presents the 18 sequential design equations used for reactor vessel and stirrer sizing. Equations 1 to 10 address vessel dimensions and wall thicknesses; Equations 11 to 18 address stirrer configuration and mechanical specifications. All equations are applied in order, with each equation's output serving as an input to subsequent calculations. The parameter $\varphi = 0.9$ in Equation 16 is the power number for a 4-blade 45° axial turbine in the turbulent flow regime at N = 100 rpm for the low-viscosity aqueous system. ASME: American Society of Mechanical Engineers.

4. Results and Discussions

4.1 Mass Balance

The mass balance for $SnCl_2$ production was computed on the basis of 1,000 kg/h tin feed, 95% Sn conversion, and stoichiometric HCl input of 2 mol HCl per mol Sn reacted. The complete component mass flows for both input and output streams are presented in Table 3. Understanding the mass balance results is essential because the total volumetric flow rate of the reactor feed directly governs the reactor sizing calculations.

Table 3. Mass balance for $SnCl_2$ production (Basis: 1,000 kg/h Sn feed, 95% conversion)

Component	Input Mass (kg/h)	Input Molar Flow (kmol/h)	Output Mass (kg/h)	Output Molar Flow (kmol/h)
Sn	1,000.00	8.4239	50.00	0.42

Component	Input Mass (kg/h)	Input Molar Flow (kmol/h)	Output Mass (kg/h)	Output Molar Flow (kmol/h)
HCl	614.27	16.8478	30.71	0.84
$SnCl_2$	0	0	1,517.31	8.00
H_2	0	0	16.13	8.00
TOTAL	1,614.27	25.2717	1,614.15	17.26

Table 3 show the mass balance is computed from the stoichiometry of $Sn + 2HCl \rightarrow SnCl_2 + H_2$ with 95% Sn conversion. The input HCl mass of 614.27 kg/h equals 16.8478 kmol/h, computed as 2 x 8.4239 x 0.95 = 16.0054 kmol/h reacted plus 0.8424 kmol/h stoichiometric excess corresponding to 5% unreacted Sn. The small discrepancy between total input (1,614.27 kg/h) and total output (1,614.15 kg/h) reflects computational rounding to four decimal places in intermediate calculations and confirms mass balance closure within 0.01%. Source: Authors' computational calculations using Microsoft Excel.

The mass balance results confirm that 1,000 kg/h Sn and 614.27 kg/h HCl at 95% conversion yield 1,517.31 kg/h $SnCl_2$ as the primary product and 16.13 kg/h H_2 as the gaseous byproduct. The unreacted fraction consists of 50 kg/h Sn (5% of feed) and 30.71 kg/h residual HCl, both of which exit in the product liquid and require management in downstream processing. The residual HCl must be neutralized before $SnCl_2$ product discharge to prevent contamination of the crystalline product, and the H_2 gas must be handled through a sealed reactor headspace and appropriate ventilation system, as hydrogen is flammable at concentrations above 4% in air (Wulandari et al., 2021; Tajuddin et al., 2021).

The $SnCl_2$ product yield of 1,517.31 kg/h corresponds to 1.517 tonnes per hour, which at 8,000 operating hours per year yields an annual production capacity of approximately 12,140 tonnes $SnCl_2$. This production scale is relevant to the Indonesian market for tin derivatives, where domestic demand for $SnCl_2$ in electroplating and manufacturing applications currently exceeds domestic production, with the shortfall met by imports (Rahmawati et al., 2022; Sudarmadi et al., 2023). The total mass input-output balance closure (0.01% discrepancy) confirms the internal consistency of the stoichiometric calculations and validates the molar flow rates used as inputs to the reactor sizing calculations.

4.2 Reactor Design Calculations and Results

The sequential application of Equations 1 to 18 to the input specifications in Table 1 and the mass balance results in Table 3 produced the complete set of reactor and stirrer design parameters presented in Table 4. Each calculated value is a direct output of the corresponding equation in Table 2, with values propagated sequentially through the equation chain. The design calculations were implemented in Microsoft Excel with full formula traceability, allowing straightforward modification of input parameters for sensitivity analysis or design iteration (Towler & Sinnott, 2022).

Table 4. Batch reactor and stirrer design parameters: Calculated results

Parameter	Calculated Value
Total reactor volume (Vr)	29.0184 ft^3
Vessel inner diameter (di)	2.7889 ft
Outer diameter after standardization (do)	2.8017 ft
Liquid volume in cylinder (Vlc)	21.5758 ft^3
Liquid height in cylinder (Hlc)	3.5337 ft
Design pressure (Pi)	13.0035 psig
Cylinder wall thickness (tc)	0.0770 in
Cylinder height (Hc)	4.1833 ft
Top lid thickness (tht)	0.0753 in

Parameter	Calculated Value
Top lid height (ht)	5.6559 in
Bottom lid thickness (thb)	0.0915 in
Bottom lid height (hb)	9.6725 in
Total reactor height (Hr)	5.6690 ft
Impeller diameter (Da)	16.7334 in
Impeller clearance from tank bottom (Zi)	11.1556 in
Impeller blade length (l)	4.1833 in
Impeller blade width (W)	3.3467 in
Number of stirrers (n)	1
Stirring power required (H)	2 Hp
Stirrer shaft diameter (D)	0.9626 in
Stirrer shaft length (L)	4.0736 ft

Table 4 show all dimensional values are reported in US customary units consistent with ASME pressure vessel design standards. The outer diameter (do) is obtained by adding twice the wall thickness (tc) to the inner diameter (di). The total reactor height (Hr) is computed as the sum of cylinder height (Hc), top lid height (ht), bottom lid height (hb), and the safety clearance factor (Sf = 2.5 in). Source: Authors' computational analysis using Microsoft Excel.

4.3 Discussion of Reactor Vessel Dimensions

The total reactor volume of 29.0184 ft^3 is approximately 35% larger than the liquid volume (21.5758 ft^3), reflecting the 80% liquid fill design constraint embedded in Equation 1. This headspace is physically important for the Sn-HCl system: the dissolution reaction generates H_2 gas that must be accommodated in the headspace before removal through the gas outlet, and the exothermic reaction may cause localized boiling at the Sn particle surfaces at 80°C, requiring space for foam and vapor Tajuddin et al., 2021. The 80% fill factor is consistent with standard batch reactor design practice for gas-generating and exothermic reactions (Walas, 1990; Towler & Sinnott, 2022).

The vessel inner diameter of 2.7889 ft (approximately 848 mm) and total height of 5.6690 ft (approximately 1,728 mm) yield a height-to-diameter ratio (H/D) of approximately 2.03. This H/D ratio is within the standard range of 1.5 to 3.0 for batch reactor vessels processing low-viscosity liquids, providing a balance between adequate mixing depth for the stirrer and reasonable vessel proportions that minimize material requirements per unit of volume (Paul et al., 2004; Nienow et al., 2022). Vessels with lower H/D ratios are more squat and may be preferred when headspace is less critical, while vessels with higher H/D ratios can improve mixing quality in tall slender configurations.

The cylinder wall thickness of 0.0770 in (1.96 mm) satisfies the ASME Section VIII Division 1 pressure vessel code for the 13.0035 psig design pressure with the stainless steel SA 240 Grade M Type 316 construction material (f = 18,750 psi) and double welded butt joint efficiency (E = 0.8), including the 0.0625 in corrosion allowance. The low design pressure (less than 15 psig) reflects the near-atmospheric operating conditions of the batch reactor, which reduces wall thickness requirements and associated material costs compared to higher-pressure applications. The conical bottom lid, with its thicker wall (thb = 0.0915 in) compared to the cylinder and dished top lid, reflects the higher stress concentration factor in the conical section from the ASME formula in Equation 9, where the $\cos(\alpha)$ term in the denominator increases the required thickness at the apex angle of 120° (Bhadeshia & Honeycombe, 2017; Towler & Sinnott, 2022).

The conical bottom cover geometry (apex angle 120°, equivalent to a 60° half-angle) serves dual purposes in the $SnCl_2$ production application. First, the sloped conical surface facilitates gravity drainage of the liquid $SnCl_2$ product and any remaining solids at the end of the batch cycle, reducing residual holdup and simplifying reactor cleaning between batches. Second, the conical geometry is preferred over flat bottom covers for solid-liquid systems because it reduces dead zones where unreacted Sn particles could settle and accumulate outside the stirrer's active mixing zone Paul et al., 2004. This is consistent with the design choices documented by Sodha et al. (2020) for their copper extraction batch reactor, where bottom geometry was identified as a significant factor in solid suspension efficiency.

4.4 Discussion of Stirrer Design

A single stirrer (n = 1) is sufficient for the designed vessel, as confirmed by the number-of-stirrers equation (Equation 15): n = Hlc / (2.5 x Da) = 3.5337 ft / (2.5 x 1.3944 ft) = 1.01, which rounds up to 1. This result confirms that the single impeller provides adequate axial flow coverage throughout the liquid height, since the liquid height is approximately 2.53 times the impeller diameter, which falls within the typical single-impeller coverage range of 2 to 3 impeller diameters Paul et al., 2004. Had the liquid height been greater relative to the impeller diameter (typically $H/D > 3$), a second impeller would have been required to ensure adequate mixing in the upper portion of the liquid.

The 4-blade 45° axial turbine with impeller diameter of 16.7334 in (approximately 425 mm) is an appropriate configuration for solid-liquid mixing in the Sn-HCl dissolution system. The 45° blade pitch creates a combination of axial and radial flow that promotes both bottom-to-top liquid circulation (preventing particle settling) and radial dispersion of the dissolved HCl and dissolved $SnCl_2$ species throughout the vessel (Paul et al., 2004; Nienow et al., 2022). The impeller clearance from the tank bottom of 11.1556 in (Zi = di/4) positions the impeller within the lower third of the liquid volume, consistent with the standard practice for solid suspension applications where the primary mixing objective is to maintain settling particles in suspension Paul et al., 2004.

The stirring power requirement of 2 Hp reflects the relatively low viscosity of the aqueous Sn-HCl reaction mixture at 80°C and the modest vessel scale. The power number $\varphi = 0.9$ applied in Equation 16 corresponds to the 4-blade 45° axial turbine operating in the turbulent flow regime (high Reynolds number) typical for low-viscosity aqueous systems at 100 rpm Paul et al., 2004. The 2 Hp motor specification includes a 25% mechanical efficiency correction that accounts for bearing and seal losses in the stirrer drive system. This relatively low power requirement is consistent with aqueous batch systems of similar scale documented in the literature, where stirring power rarely exceeds 5 Hp for vessels under 30 ft^3 with low-viscosity contents (Talaghat et al., 2020; Sodha et al., 2020).

The shaft diameter of 0.9626 in (approximately 24.5 mm) was determined from the torsional stress design criterion in Equation 17: $D = (16T / \pi S)^{(1/3)}$, where the torsion moment T is derived from the stirring power H and shaft rotational speed, and S is the maximum allowable shearing stress for the Hot Roller Steel SAE 1020 shaft material. The shaft length of 4.0736 ft positions the impeller at the correct clearance above the conical bottom while keeping the shaft top above the liquid surface for connection to the motor drive assembly. The choice of SAE 1020 hot-rolled carbon steel for the shaft provides adequate torsional strength for the 2 Hp load at a substantially lower cost than the stainless steel used for the impeller blades, which are in direct contact with the corrosive HCl solution Bhadeshia & Honeycombe, 2017.

4.5 Implications for Industrial $SnCl_2$ Production in Indonesia

The batch reactor design parameters in Table 4 provide a validated computational basis for the engineering assessment of an industrial $SnCl_2$ production facility operating on Indonesian tin feedstock. The design confirms the practical feasibility of producing 1,517 kg/h $SnCl_2$ (approximately 12,140 tonnes per year at 8,000 operating hours) in a single batch reactor of manageable dimensions, processing 1,000 kg/h Sn from Bangka-Belitung tin resources (Rahmawati et al., 2022; Sudarmadi et al., 2023). The vessel dimensions and material specifications are consistent with what can be fabricated by Indonesian heavy equipment manufacturers, and the 2 Hp stirring power requirement indicates low energy consumption relative to the production volume.

The design parameters can be used directly by process engineers to specify reactor fabrication, evaluate construction costs, and size auxiliary equipment. For the Sn-HCl system specifically, auxiliary equipment sizing should address the HCl solution feed system with appropriate acid-resistant pumps, the H_2 gas handling system requiring sealed headspace and dilution ventilation to maintain H_2 below the lower flammability limit of 4%, the product discharge and crystallization system for converting the liquid $SnCl_2$ product to solid form, and a heat management system for the exothermic dissolution reaction to maintain the 80°C operating temperature without thermal runaway (Wulandari et al., 2021; Tajuddin et al., 2021). Future economic feasibility studies should build on these design parameters to evaluate capital cost, operating cost, and the economic return on downstream tin processing investment for Indonesian tin producers.

The batch reactor configuration chosen for this design offers important operational advantages for the Indonesian industrial context. Batch operation provides flexibility to adjust production volume in response to market demand without the capital investment constraints of a continuous plant designed for a fixed throughput. The relatively simple construction of a batch vessel compared to a continuous reactor train reduces the technical barriers to entry for Indonesian manufacturers seeking to develop downstream tin processing capacity. Additionally, batch operation allows the use of tin feedstocks with variable particle size distributions, as the longer residence time relative to a continuous system is more tolerant of feedstock variability (Roy & Aditya, 2015; Karagoz et al., 2019; Nandiyanto et al., 2023).

5. Conclusions

5.1 Conclusion

This study successfully designed a batch reactor for the industrial-scale production of stannous chloride ($SnCl_2$) particles from Indonesian tin resources using a systematic computational approach based on sequential chemical engineering design equations. The mass balance on a 1,000 kg/h Sn feed basis with 95% Sn conversion confirmed production of 1,517.31 kg/h $SnCl_2$ and 16.13 kg/h H_2, with total mass balance closure within 0.01%. The resulting reactor specifications are: total volume 29.0184 ft^3, inner diameter 2.7889 ft, total height 5.6690 ft, and cylinder wall thickness 0.0770 in, fabricated from stainless steel SA 240 Grade M Type 316 with a double welded butt joint. The reactor incorporates a single axial turbine stirrer with four blades at 45°, an impeller diameter of 16.7334 in, 2 Hp stirring power, shaft diameter of 0.9626 in, and shaft length of 4.0736 ft. The design conforms to ASME Section VIII Division 1 pressure vessel standards for the 13.0035 psig design pressure and the corrosive service environment. The calculated parameters provide a directly applicable engineering basis for the construction and commissioning of an industrial $SnCl_2$ production facility, supporting Indonesia's strategic objective of increasing the domestic value added from its tin mineral resources through downstream chemical processing.

5.2 Research Limitations

Several limitations bound the scope and applicability of the present design study. First and most significantly, the reactor sizing calculations were performed without incorporating the Sn-HCl reaction effectiveness factor (η), which accounts for internal mass transfer resistance (intraparticle diffusion) within the solid tin particles. For the heterogeneous solid-liquid reaction system, the true conversion rate may be lower than the intrinsic chemical kinetic rate if diffusion of HCl through the product layer on tin particle surfaces is rate-limiting at industrial scale, particularly for coarser particle size fractions. Neglecting η means the design conservatively assumes that the full particle surface area is accessible to HCl, and that the 1-hour batch time is sufficient to achieve 95% conversion regardless of particle size. Validation against experimental data at batch scale would be needed to confirm this assumption. Second, the design assumes ideal mixing throughout the vessel, meaning that the stirrer provides sufficient agitation to maintain uniform concentration and temperature at all points in the liquid volume. In practice, the dissolution of solid Sn particles may create local concentration gradients near the Sn surface that reduce the effective driving force for reaction, particularly at high solids loading. Third, the design does not address the thermal management requirements for the exothermic Sn-HCl reaction: heat generation from the dissolution reaction at 80°C must be removed or managed to prevent uncontrolled temperature rise, requiring a heat exchanger or jacket specification that is beyond the scope of the present calculations. Fourth, the study is limited to vessel and stirrer sizing and does not address the downstream crystallization unit, gas handling system, or product drying equipment that would be required for a complete $SnCl_2$ production facility.

5.3 Directions and Future Study

Future research should address the documented limitations through several specific development directions. The effectiveness factor for the Sn-HCl reaction should be measured experimentally across the particle size range of practical interest (100 to 500 mesh's) and at the operating temperature of 80°C, providing the data needed to refine the reactor sizing calculations and the batch time required for the 95% conversion target. Computational Fluid Dynamics (CFD) simulation of the stirred vessel should be employed to verify the assumption of ideal mixing and to identify any dead zones or settling regions that may require design modifications, building on the CFD approaches used in analogous solid-liquid reactor design studies. The exothermic heat of reaction for the Sn-HCl dissolution should be measured calorimetrically and incorporated into a heat balance, from which the required heat exchanger or jacket area can be sized to maintain the 80°C operating temperature. A complete process design extending beyond the batch reactor to include the crystallization step for solid $SnCl_2$ product recovery, the gas handling system for H_2, and the acid neutralization treatment for waste streams would provide the comprehensive engineering basis needed for a full economic feasibility study. Finally, an economic analysis of the $SnCl_2$ production facility, building on the reactor design parameters from this study, should be conducted to quantify the capital investment, production cost, and economic return from downstream tin processing in Indonesia, supporting policy decisions about incentives for tin industry diversification.

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Author Contributions

YIBPN contributed to conceptualization, formal analysis, methodology, calculations, data curation, writing (original draft). RR contributed to supervision, review and editing, validation, resources. ABDN contributed to supervision, funding acquisition, project administration, review and editing, validation.

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