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Simulation of an 18 MW Alkaline Electrolysis Plant for Green Hydrogen Production in Abu Dhabi

[1]Fatoumah Aidaros Al-Hebshi, [1,2]Badiea S. Babaqi*, [1]Reem Moajeb Bakhteeb, [1]Raqia Ali Taofan, [1]Shahid Khalid Bin Saleh, [1]Fatema Omer Mhymod

[1]Department of Chemical Engineering, Faculty of Engineering and Petroleum, Hadhramout University, Yemen

[2]Research Centre for Sustainable Process Technology, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Malaysia

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****Corresponding Author:***
Badiea S. Babaqi
dr.badieababaqi@hu.edu.ye

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Abstract

In the global effort to combat climate change and reduce greenhouse gas emissions, the creation of green hydrogen by water electrolysis powered by renewable energy sources, such as solar power, is becoming more important. In order to take advantage of the rich solar energy resources in the Al Dhafra region and offer sustainable electricity for the plant's hydrogen production operations, this research presents a simulation and analysis of an alkaline electrolysis plant located in Abu Dhabi. Based on basic chemical engineering design concepts, the research performs extensive calculations for the material and energy balances and estimates the capital costs of the process equipment. The findings show that the proposed alkaline electrolysis facility can produce hydrogen at a rate of 3753 kg/h and, as a beneficial byproduct, 28906 kg/h of oxygen. It is expected that an 18 MW alkaline electrolysis plant will require a total capital investment of about 100,000,000 USD, with an approximate yearly profit predicted of this process that reached of 50,000,000 USD. This analysis supports the region's sustainability goals and the global shift to a low-carbon future by highlighting the economic feasibility and environmental advantages of including the renewable energy-powered green hydrogen generation into Abu Dhabi's energy landscape.

1. Introduction

Endeavors are being made around the world to decrease carbon emissions with the aim of decreasing global warming. The green hydrogen generated from water electrolysis powered by renewable energy is becoming increasingly important in the production of clean hydrogen. As the shift to renewable energy for clean energy sources demands, green hydrogen production must be greatly increased to make it more economical and sustainable.

Using solar energy from the Al-Dhafra solar project to generate hydrogen in an alkaline electrolysis plant is considered a proposed project. The global weighted-average total installed cost of solar PV projects decreased by approximately 67%, dropping from 2652 USD/KW in 2014 to 876 USD/KW in 2022, and the cost in 2022 saw a further decline of around 4% compared to the value in 2021 [1]. The Al-Dhafra PV power facility has a total capacity of 2GW, and it produces an estimated 7 TWh of energy annually at a rate of 13.2 USD/MWh [2]. One of the most important challenges facing renewable energy sources is the limited energy storage capacity, as energy cannot be stored very efficiently, which means that users must use it immediately after it is generated. As well as the challenges of energy transportation, as energy must be transferred from the areas where it is generated to the areas that need it, which requires large infrastructure and high costs. Another challenge is that electrons generated from solar energy, for example, cannot operate iron and steel factories. However, these electrons can generate electricity to separate water molecules in the electrolyzer cell (alkaline cell) to generate hydrogen. This hydrogen works as an excellent carrier of energy and can provide power to large industries.

There are many opportunities offered by green hydrogen plants; for example, the solar energy company in Al Dhafra can store energy derived from renewable sources in hydrogen. Also, it can export it to countries that lack renewable energy sources, which contributes to strengthening the economy of the UAE [2]. As the value of green hydrogen produced from an alkaline electrolysis is 2.9 $/kg [3]. Green hydrogen also reduces the carbon footprint of heavy industries with high environmental pollution. In addition, it is used in advanced means of transportation, such as aviation and marine industries, using hydrogen cells. As well as transportation vehicles such as cars and trains, the current fuel cell technology allows hydrogen to power a wide range of vehicle types [4]. That will contribute to achieve sustainable development goals and reducing carbon emissions in the UAE.

The aim of this work is to simulate an 18 MW alkaline electrolysis plant in Abu Dhabi using aspen Plus®, utilizing renewable solar energy to produce green hydrogen, and to evaluate the process's material and energy balances, capital costs, and potential profitability.

2. Methodology

The simulation process of an alkaline electrolysis plant was carried out via mass and energy balances for the production of green hydrogen via alkaline electrolysis using Aspen Plus®. The economic analysis was conducted to define the total module cost for predicting the cost estimation of the process according to the Chemical Engineering Plant Cost Index (CEPCI) in 2023.

2.1. Simulation of Alkaline Electrolysis Plant

The model of an alkaline water electrolysis system has been developed using Aspen Plus® [5], including the alkaline electrolysis cell stack and the balance of plant (BOP). The simulation diagram of the AEL plant studied is shown in Figure (1). The electrolyte with a 35% potassium hydroxide (KOH) solvent enters the parallel cells equally. In our research, we have applied the principle of scale-up to the simulation results to make them suitable for industrial production. 18 MW of electricity from PV is applied to the alkaline electrolyzer with 20,000 parallel cells [6]. The electrolyte is converted into hydrogen and oxygen by a water-splitting reaction.

Fresh water is fed from a water tank into the oxygen separator (V-101) by a pump (P101) to provide water for the electrolysis process. Hydrogen and oxygen produced in the stack are led with the electrolyte to the liquid-gas separation vessels (V-101 and V-102), where the electrolyte is separated from the gas and returned back to the stack by recirculation pumps (P-102 and P-103). Both KOH recycles pass through plate heat exchangers (E-101 and E-102) to cool down the electrolyte before entering the stack. The hydrogen and oxygen that are separated in the separation vessels are passed through water traps (TRAP-101 and TRAP-102) to eliminate the maximum amount of condensate water. Hydrogen gas is produced with a purity of 99.25%. Finally, we introduce a hydrogen dryer to increase the purity of the gas by reducing the moisture content in the hydrogen produced from the trap [7]. The final product is green hydrogen with a purity of 99.9%, which is suitable for industrial purposes. Reactions occur inside the cell:

Reaction in cathode: $4e + 4H_2O \rightarrow 2H_2\uparrow + 4OH^-$

Reaction in anode: $4OH^- \rightarrow 2H_2O + O_2\uparrow + 4e$

Over all reaction: $2H_2O \rightarrow 2H_2\uparrow + O_2\uparrow$

2.2. Capital Costs Estimations for Process Equipment

We used design considerations in chemical engineering for the process equipment to calculate the capital cost of the plant [8].

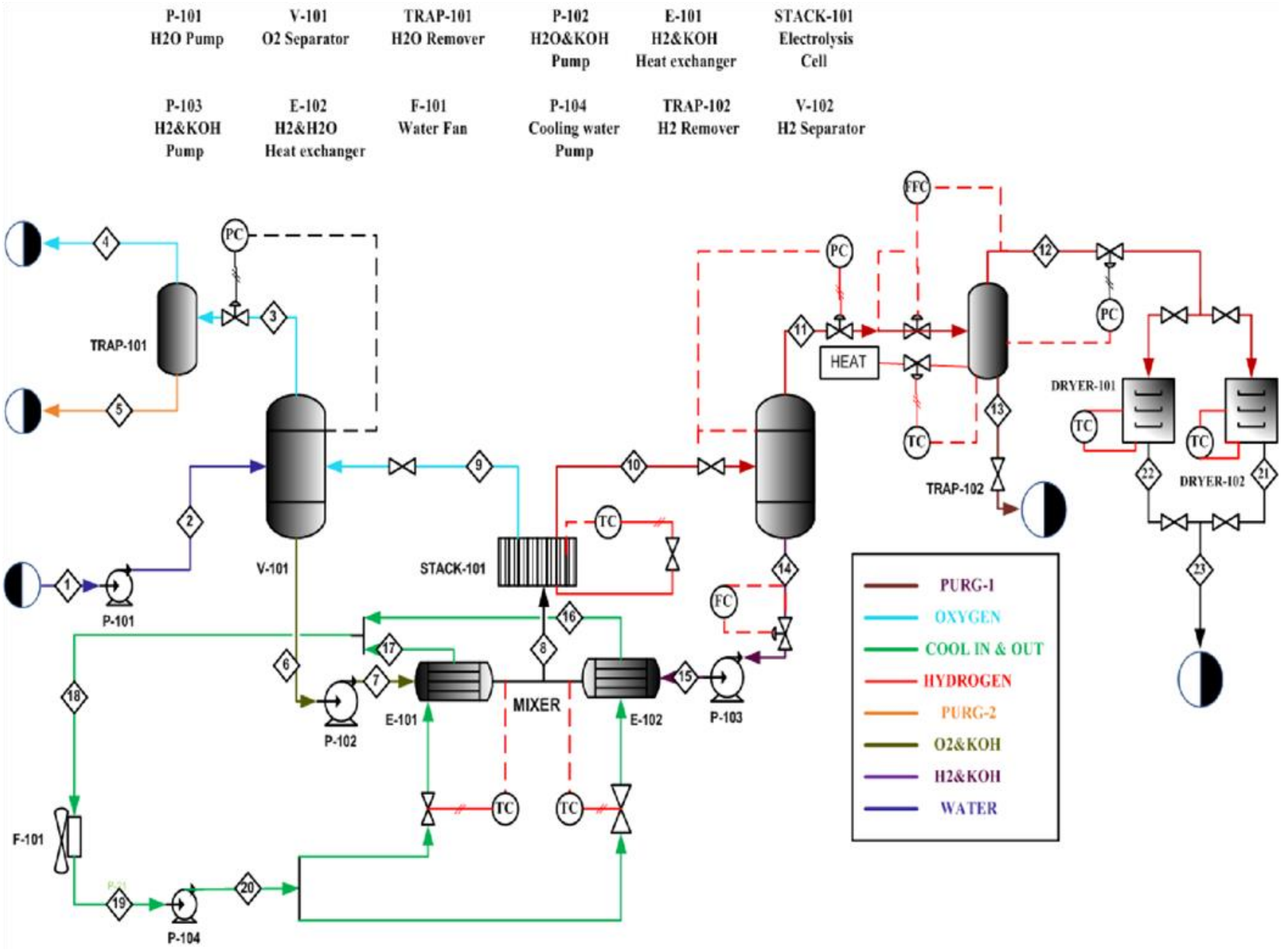

Figure (1): Simulation of the proposed plant flow sheet.

2.3. Cost Calculation Method

2.3.1. Fixed Capital Investment

Knowing the costs of the primary plant equipment is necessary to estimate the capital cost of a chemical plant. A standard method for estimating the price of a new chemical plant is the equipment module costing technique [8].

$$\mathbf{CBM = CP^{\circ}\ FBM = CP^{\circ}\ (B1 + B2FMFP)}$$

Where: CBM: bare module equipment cost: direct and indirect costs, CP°: purchased cost for base conditions, and B1, B2: Constants depend on type of equipment. Data for the purchased cost of the equipment C_P° were fitted to the following equation:

$$\mathbf{\log_{10} C_P^{\circ} = K_1 + K_2 \log_{10}(A) + K_3[\log_{10}(A)]^2}$$

Where: A: the capacity or size parameter for the equipment given in Table (1) in appendix [8]. K_1 , K_2 , and K_3 are constants given in Table (2) in appendix [8].

$$\mathbf{Pressure\ Factor\ F_P:\ F_P = \frac{\frac{PD}{2SE-1.2P}+CA}{t_{min}}}$$

Where: P: the design pressure (barg), D: the diameter of the vessel (m), S: the maximum allowable pressure (maximum allowable stress) of material (bar), E: weld efficiency dependent on the type of weld and the degree of examination and typical values are from 1.0 to 0.6), CA: the corrosion allowance (m) depends on the service, and typical values are from 3.15 to 6.3 mm, and $\mathbf{t_{min}}$: the minimum allowable vessel thickness (m). For different equipment:

$$\log_{10} F_P = C_1 + C_2 \log_{10}(P) + C_3[\log_{10}(P)]^2$$

Where: C_1, C_2, C_3: Constant given in Table (3) in appendix [8].

Material Factors F_M:

They are given in Figures (2 & 3), with the appropriate identification number listed in Tables (4) and (5) in appendix [8]. It is essential to be able to update these costs to take changing economic conditions (inflation) into account. This can be achieved by using the following expression:

$$C_2 = C_1\left[\frac{I_{2023}}{I_{2001}}\right]$$

Where: **C:** Purchased cost, **I:** Chemical Engineering Plant Cost index (CEPCI), a number that relates the cost of an item at a specific time to the corresponding cost at some arbitrarily specified time in the past. $\mathbf{I_{2023}}$ = 801.4. After calculating the bare module cost, the total module cost can be calculated by the following equations:

$$C_{TM} = \sum_{i=1}^{n} C_{TM,i} = 1.18 \sum_{i=1}^{n} C_{BM,i}$$

$$C_{GR} = C_{TM} + 0.50 \sum_{i=1}^{n} C^{\circ}_{BM,i}$$

Table (6): Input flow sheet equipment information for CAPCOST.

Equipment No.	**V-101 O_2Separator**	**V-102 H_2 Separator**	**E-101 Electrolyte Heat Exchanger**	**E-102 Electrolyte Heat Exchanger**	**Trap-101 Oxygen Trap**	**Trap-102 Hydrogen Trap**	**P-102 Electrolyte Pump**	**P-103 Electrolyte Pump**	**P-104 Cooling Water Pump**	**F-101 Cooling Water Fan**
Capacity/Size	D=2.5m H=7.5 m Vertical Vessel	D=2.5 m H=7.5 m Vertical Vessel	Area= 84.71 m^2 Flat Plate	Area= 84.71 m^2 Flat Plate	D=1 m H= 3.5 m	D=1 m H= 3.5 m	Power=109.64 kw Centrifugal	Power=108.7 kw Centrifugal	Power=38.35 kw Centrifugal	Flow rate=19.21 m^3/s Centrifugal Radial
MOC.	CS	CS	SS	SS	SS	SS	Cast Iron	Cast Iron	Cast Iron	CS
Operating Pressure (barg)	7	7	7	7	6.7	6.7	6.7	6.7	1	1

2.3.2. Operating Cost

The cost of manufacturing, COM, can be determined when the following costs are known: Fixed capital investment (FCI), Cost of operating labor (COL), Cost of utilities (CUT), Cost of waste treatment (CWT), and Cost of raw material (CRM) [8].

$$\mathbf{COM = 0.280FCI + 2.73\ COL + 1.23(CUT+CWT+CRM)}$$

2.3.3. Total Capital Investment

Total capital investment = fixed capital cost + operating cost

2.3.4. Income of Profit

Profit = Sales Income – Operating Cost

3. Results and Discussion

For the purpose of process evaluation to produce green hydrogen, a summary of results for simulating was developed as given in Table (7). It can be seen that the hydrogen reached 3753 kg/h.

Table (7): Amounts of raw materials and products and their costs.

Raw materials and products	Amount	Cost ($/Kg)	Cost	Yearly Cost ($/y)
Feed Water to Stack (Kg)	12699131	0.053	673054 $	673054
Make-Up Water (Kg/h)	35666.5	0.053	1890 $/h	15,728,580
KOH Powder (Kg)	6798250	1.1	7478075 $	7,478,075
Hydrogen Production (Kg/h)	3753	2.9	10884 $/h	90,574,150
Oxygen Production (Kg/h)	28906	2.235	64605 $/h	537,642,061

For capital cost estimation of process equipment, the results are reported in Table (8). It can be seen that in the total capital investment cost estimation, the plant reaches approximately 100,000,000 USD, and the annual profit is approximately 50,000,000 USD per year.

Table (8): Result of cost estimation.

Fixed Capital Investment (USD)	Operating Cost (USD)	Total Capital Investment Cost (USD)	Income of Profit (USD/year)
59,500,000	40,500,000	100,000,000	50,000,000

3.1. Cost and Risk Assumptions

Reducing the cost of producing green hydrogen is achieved by: improving the efficiency of alkaline cells, reducing the cost of raw materials, improve system design and optimize the cost of renewable energy.

There are many technical and operational risks associated with hydrogen production such as: chemical leakage, unexpected chemical reaction, charging problems, reverse connection and ambient environment corrosion [7].

To mitigate these risks, several preventive measures can be taken including: proper storage of batteries in a cool and dry place away from flammable materials, periodic examination to ensure there is no damage or leakage, careful handling by follow the instructions for charging and discharging, and proper disposal of spent batteries appropriately in accordance with local waste disposal regulations [7].

4. Conclusions

The future with green hydrogen holds great promise for addressing climate change and transitioning to a more sustainable energy system. Using an 18 MW plant to operate the alkaline electrolysis plant in Abu Dhabi will produce 3753 kg/h of green hydrogen. For total capital investment cost estimation, the plant reaches approximately 100,000,000 USD and the annual profit is approximately 50,000,000 USD per year.

Conflict of Interest: The authors declare that there are no conflicts of interest regarding the publication of this paper. All authors have contributed to the research work and manuscript preparation without any financial, personal, or professional affiliations that could be perceived as influencing the presented research.

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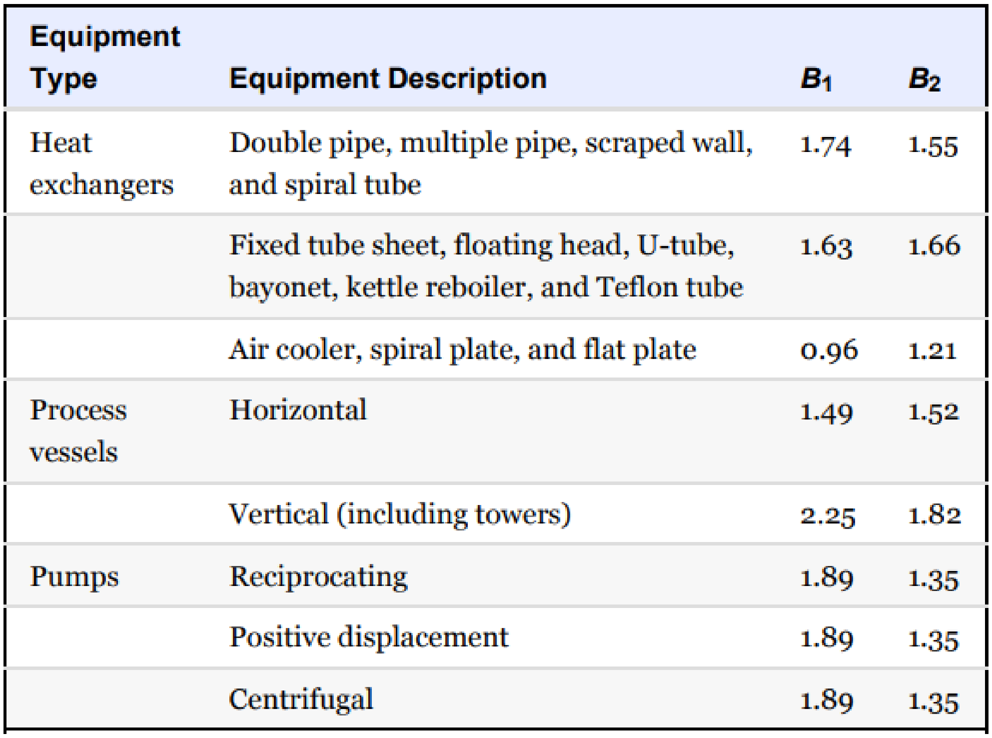
Appendix:

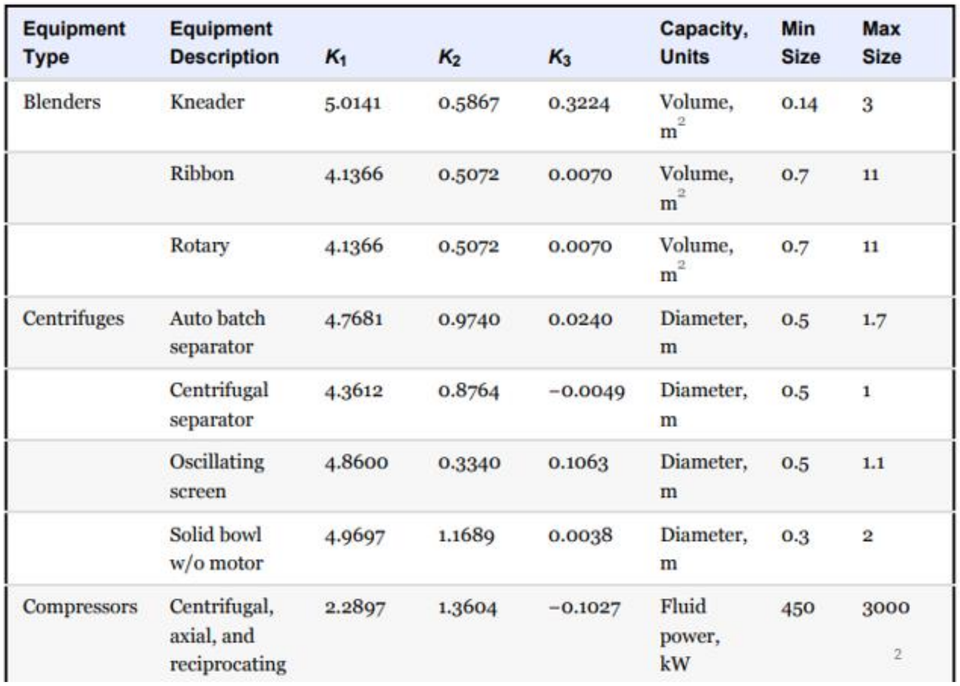
1. List of Tables:

Table (1): Constants for Bar Module factor (source: [8]).



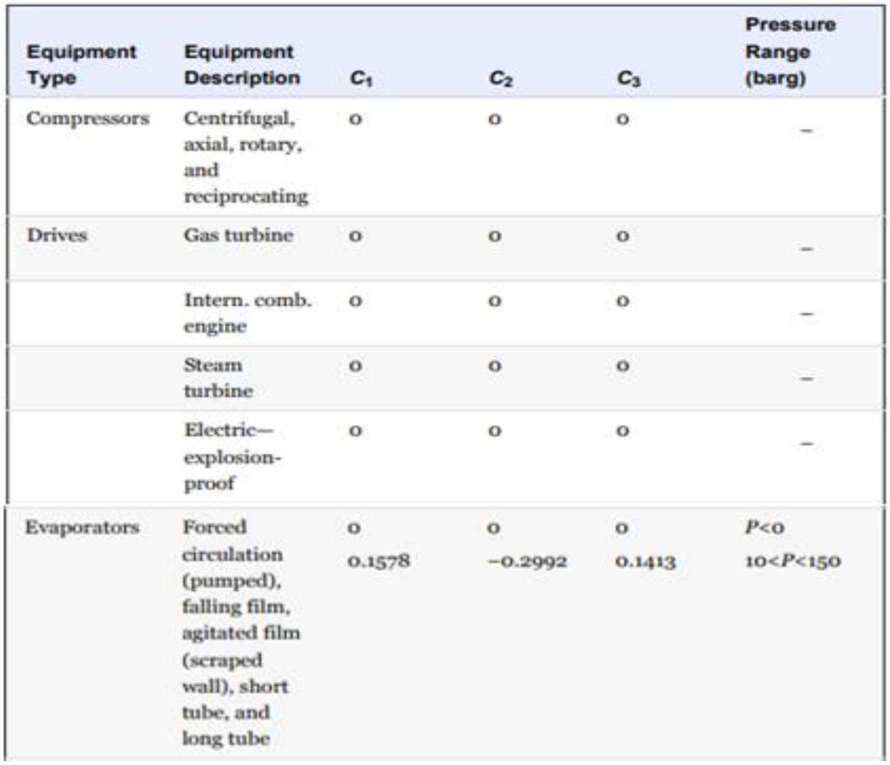
Equipment Type	Equipment Description	B_1	B_2
Heat exchangers	Double pipe, multiple pipe, scraped wall, and spiral tube	1.74	1.55
	Fixed tube sheet, floating head, U-tube, bayonet, kettle reboiler, and Teflon tube	1.63	1.66
	Air cooler, spiral plate, and flat plate	0.96	1.21
Process vessels	Horizontal	1.49	1.52
	Vertical (including towers)	2.25	1.82
Pumps	Reciprocating	1.89	1.35
	Positive displacement	1.89	1.35
	Centrifugal	1.89	1.35

Table (2): Equipment cost data (source: [8]).



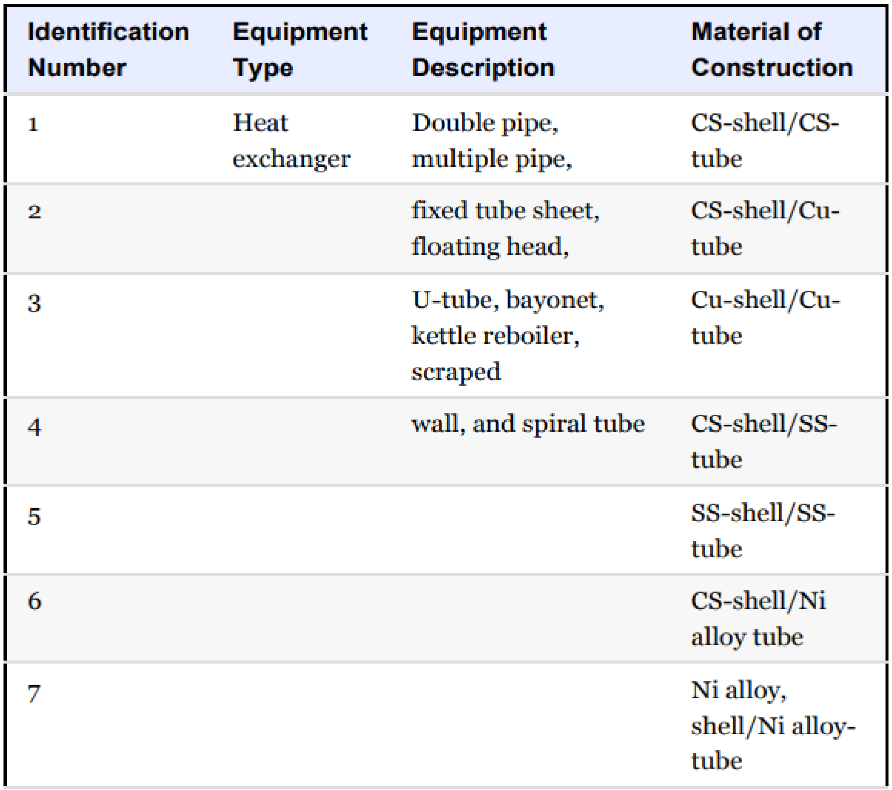
Equipment Type	Equipment Description	K_1	K_2	K_3	Capacity, Units	Min Size	Max Size
Blenders	Kneader	5.0141	0.5867	0.3224	Volume, m^2	0.14	3
	Ribbon	4.1366	0.5072	0.0070	Volume, m^2	0.7	11
	Rotary	4.1366	0.5072	0.0070	Volume, m^2	0.7	11
Centrifuges	Auto batch separator	4.7681	0.9740	0.0240	Diameter, m	0.5	1.7
	Centrifugal separator	4.3612	0.8764	−0.0049	Diameter, m	0.5	1
	Oscillating screen	4.8600	0.3340	0.1063	Diameter, m	0.5	1.1
	Solid bowl w/o motor	4.9697	1.1689	0.0038	Diameter, m	0.3	2
Compressors	Centrifugal, axial, and reciprocating	2.2897	1.3604	−0.1027	Fluid power, kW	450	3000 2

Table (3): Pressure factors for process equipment (source: [8]).



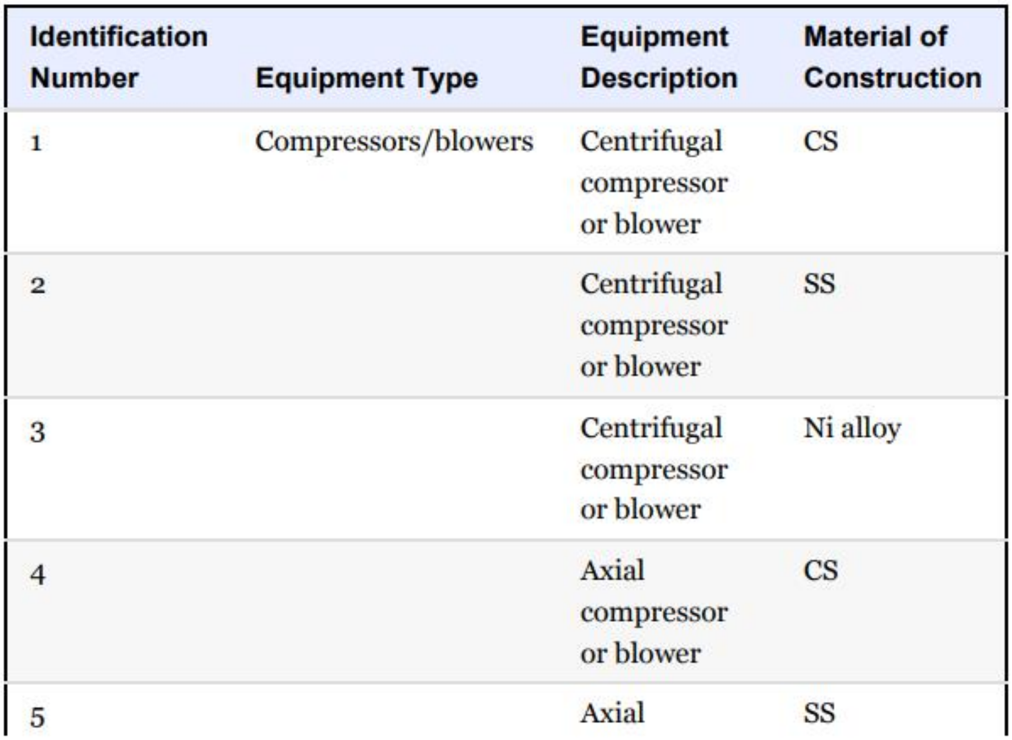
Equipment Type	Equipment Description	C_1	C_2	C_3	Pressure Range (barg)
Compressors	Centrifugal, axial, rotary, and reciprocating	0	0	0	–
Drives	Gas turbine	0	0	0	–
	Intern. comb. engine	0	0	0	–
	Steam turbine	0	0	0	–
	Electric—explosion-proof	0	0	0	–
Evaporators	Forced circulation (pumped), falling film, agitated film (scraped wall), short tube, and long tube	0 0.1578	0 −0.2992	0 0.1413	$P<0$ $10<P<150$

Table (4): Identification numbers for for material factors for heat exchangers, process vessels, and pumps to be used in Figure (2) (source: [8]).



Identification Number	Equipment Type	Equipment Description	Material of Construction
1	Heat exchanger	Double pipe, multiple pipe,	CS-shell/CS-tube
2		fixed tube sheet, floating head,	CS-shell/Cu-tube
3		U-tube, bayonet, kettle reboiler, scraped	Cu-shell/Cu-tube
4		wall, and spiral tube	CS-shell/SS-tube
5			SS-shell/SS-tube
6			CS-shell/Ni alloy tube
7			Ni alloy, shell/Ni alloy-tube

Table (5): Identification of material factorsfor equipment to be used with Figure (3) (source: [8]).



Identification Number	Equipment Type	Equipment Description	Material of Construction
1	Compressors/blowers	Centrifugal compressor or blower	CS
2		Centrifugal compressor or blower	SS
3		Centrifugal compressor or blower	Ni alloy
4		Axial compressor or blower	CS
5		Axial	SS

2. **List of Figures:**

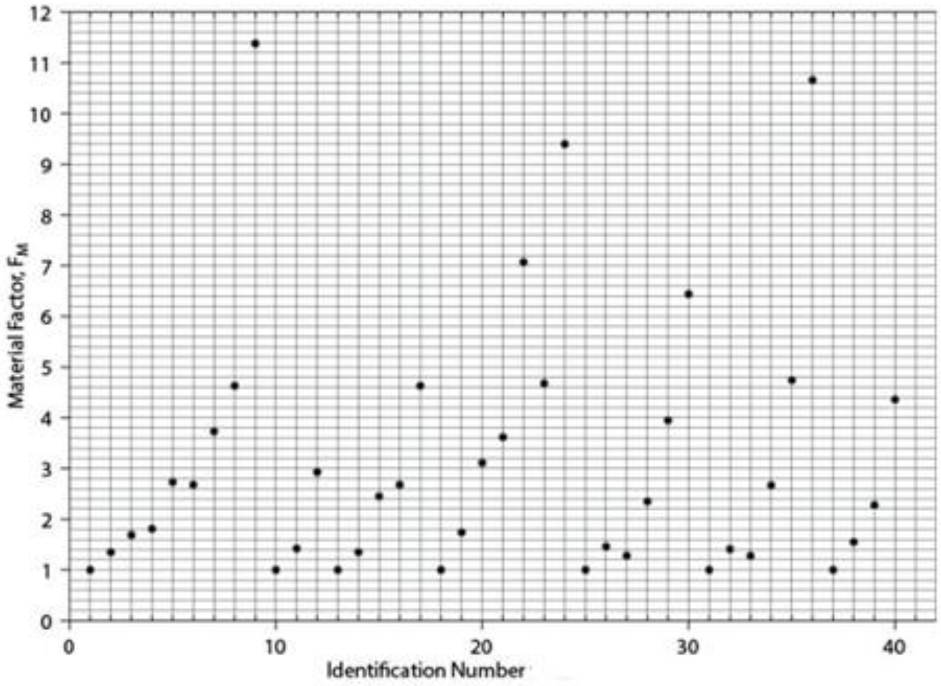


Figure (2): Material factors for equipments (source: [8]).

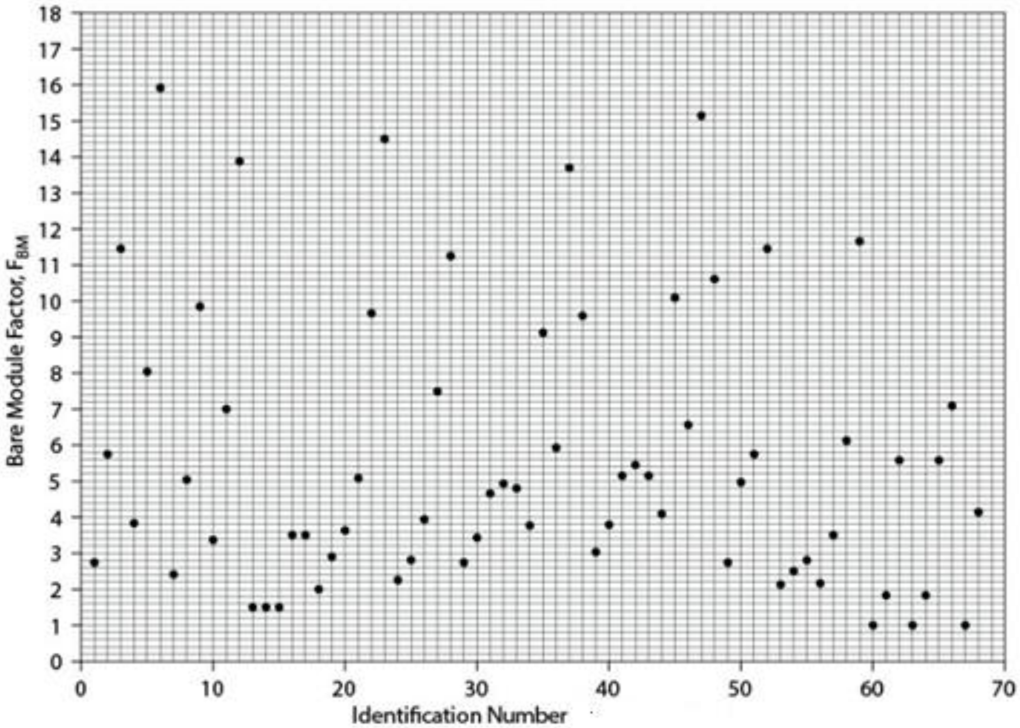


Figure (3): Bar Module factors for equipment (source: [8]).