

Supplementary data

Optimization of cryogenic nitrogen rejection process with rejected nitrogen utilization

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Appendix A.

This supplementary material presents the correlations and data required for economic evaluation, including cost estimation correlations for NRU process equipment, utilities, gas transportation, injection wells, and more.

A.1. Cost of Compressors (CEPCI₂₀₁₃ = 567)

To estimate the purchase cost of the compressor, the correlations provided by Seider et al. [1] have been used. f.o.b. purchase cost is given by:

$$C_p = F_D F_M C_B \quad (\text{A.1})$$

The base compressor purchase cost is given by the following equations with P_C in horsepower (Centrifugal compressor, valid from $P_C = 200$ to 30,000 Hp):

$$C_B = \exp\{9.1553 + 0.63[\ln(P_C)]\} \quad (\text{A.2})$$

Where

C_P (\$) = f.o.b. purchase cost

C_B (\$) = Base compressor purchase cost

F_D (-) = Motor/driver factor

F_M (-) = Material factor

P_C (Hp) = Power

A.2. Cost of Distillation Column (CEPCI₂₀₁₃ = 567)

The f.o.b. purchase cost of a typical tower for distillation is obtained by the following relations provided by Seider et al. [1]:

$$C_p = F_M C_V + C_{PL} \quad (F_M = 1.7 \text{ for material: SS304}) \quad (\text{A.3})$$

for 9,000 < W < 2,500,000 lb:

$$C_V = \exp\{10.5449 - 0.4672[\ln(W)] + 0.05482[\ln(W)]^2\} \quad (\text{A.4})$$

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for $3 < D_i < 24$ ft and $27 < L < 170$ ft:

$$C_{PL} = 341(D_i)^{0.63316} (L)^{0.80161} \quad (\text{A.5})$$

$$P_d = \exp\left\{0.60608 + 0.91615[\ln(P_o)] + 0.0015655[\ln(P_o)]^2\right\} \quad (10 < P_o < 1000 \text{ psig}) \quad (\text{A.6})$$

$$t_p = \frac{P_d D_i}{2SE - 1.2P_d} \quad S = 16000 \text{ psi}, \quad E = 0.85 \quad (\text{A.7})$$

$$t_w = \frac{0.22(D_o + 18)L^2}{SD_o^2} \quad (\text{A.8})$$

$$t_v = t_p + 0.5t_w \quad (\text{A.9})$$

$$t_c = 1/32 \text{ inch for SS} \quad \text{or} \quad 1/8 \text{ inch for CS} \quad (\text{A.10})$$

$$t_s = t_v + t_c \quad (\text{A.11})$$

$$W = \pi(D_i + t_s)(L + 0.8D_i)t_s \rho \quad (\text{A.12})$$

Where

C_p (\$) = Total f.o.b. purchase cost of distillation column without internals

C_V (\$) = f.o.b. purchase cost of the distillation column (Cost includes nozzles, manholes, and supports, but not internals (plates or packing), platforms, or ladders)

F_M (-) = Material factor

W (lb) = Weight of the shell and the two heads

C_{PL} (\$) = The added cost for platforms and ladders for towers

D_i (in) = Internal diameter

L (in) = Tangent-to-tangent length of the shell

ρ (lb/ft³ or lb/in³) = Density of the carbon steel

P_o (psig) = Operating pressure

P_d (psig) = Internal design gauge pressure

S (psi) = Maximum allowable stress of the shell material at the design temperature

E (-) = Fractional weld efficiency

t_s (in) = Shell thickness

t_v (in) = Vessel wall thickness

t_p (in) = Thickness at the top

t_w (in) = The necessary thickness to withstand the wind load or earthquake at the bottom of the column

t_c (in) = Corrosion allowance

A.3. Cost of Distillation Column Plates (CEPCI₂₀₁₃ = 567)

The cost equations for the installed trays (C_T) with downcomers are given below provided by Seider et al. [1]:

$$C_T = N_T F_{NT} F_{TT} F_{TM} C_{BT} \quad (\text{Valid for } D_i = 2 \text{ to } 16 \text{ ft, } F_{TT} = 1 \text{ for Sieve trays}) \quad (\text{A.13})$$

$$C_{BT} = 468 \exp(0.1482D_i) \quad (\text{A.14})$$

$$\text{If } N_T > 20 \rightarrow F_{NT} = 1 \quad (\text{A.15})$$

$$\text{If } N_T < 20 \rightarrow F_{NT} = \frac{2.25}{1.0414^{N_T}} \quad (\text{A.16})$$

$$F_{TM} = 1.189 + 0.0577D_i \text{ (SS303)}, \quad F_{TM} = 1.401 + 0.0724D_i \text{ (SS316)} \quad (\text{A.17})$$

Where

C_T (\$) = Cost of installed trays with downcomers

C_{BT} (\$) = Base cost for sieve trays

D_i (ft) = Inside diameter of the column

N_T (-) = Number of trays

F_{NT} (-) = Factor dependent on tray numbers

F_{TT} (-) = Factor for type of tray

F_{TM} (-) = Material factor

A.4. Cost of Shell and Tube Heat exchanger, Intercoolers and Aftercoolers (CEPCI₂₀₁₃ = 567)

The f.o.b. purchase cost for the shell and tube heat exchangers is calculated using the equations given below [1]:

$$C_p = F_p F_M F_L C_B \quad (F_L = 1.0) \quad (\text{A.18})$$

$$F_p = 0.9803 + 0.018 \left(\frac{P}{100} \right) + 0.0017 \left(\frac{P}{100} \right)^2 \quad (\text{A.19})$$

$$F_M = a + \left(\frac{A}{100} \right)^b \quad (a = 0.0, b = 0.0 \text{ for carbon steel}) \quad (\text{A.20})$$

$$\text{Floating head : } C_B = \exp \left\{ 12.0310 - 0.8709 [\ln(A)] + 0.09005 [\ln(A)]^2 \right\} \quad (\text{A.21})$$

Where

C_B (\$) = Cost of base-case exchanger

A (ft²) = Tube outside surface area (valid for $A = 150$ ft² to 12,000 ft²)

P (psig) = Shell side pressure

F_p (-) = Pressure factor (dependent on the shell-side pressure)

F_M (-) = Material factor

F_L (-) = Tube-length correction. $F_L = 1.0$ (L = 20 ft), $F_L = 1.05$ (L = 16 ft), $F_L = 1.12$ (L = 12 ft),

$F_L = 1.25$ (L = 8 ft)

Note: The base-case exchangers include 3/4-in. or 1-in. O.D., 16 BWG (Birmingham Wire Gage) carbon-steel tubes, 20 ft long, on square or triangular pitch in a carbon-steel shell for use with shell-side pressures up to 100 psig.

A.5. Cost of Multi-stream Heat Exchanger (CEPCI₂₀₁₂ = 585)

Typically, when estimating the cost of a multi-stream heat exchanger (MSHE) used for feed precooling, heat integration, or heat pump applications, the commonly used approach is the algorithm proposed by Hewitt and Pugh [2]. This algorithm primarily relies on the volume of the

multi-stream heat exchanger as the main variable for cost estimation. On the other hand, the cost estimation for shell and tube heat exchangers is typically based on the outer surface area of the tubes. However, in the present study, a different cost estimation method for multi-stream heat exchangers is utilized, as described in reference [3]. This method takes into account the cost proportional to the heat exchanger surface, which is calculated using the Aspen HYSYS software.

$$MSHE \text{ cost} = 425 \times A \quad (\text{A.22})$$

Where

A (m^2) = Surface area

A.6. Utilities (2023)

The cost of electricity and cooling water is obtained using the following equations:

Electricity Industrial Sector avg-2023 = 8.3 cents/kW.hr (From [4])

$$\text{Electricity cost} = \left(\sum_i \text{Power}_i \right) \times 0.083 \times 8000 \quad (\text{A.23})$$

Cooling water (tower) = 2-3 cents/ m^3 (From [5,6], in 2023)

$$\text{Cooling water cost} = \left(\sum_i \text{Flowrate}_i \right) \times 0.025 \times 8000 \quad (\text{A.24})$$

A.7. Transportation cost

In order to calculate capital costs, Eq. (A.25) is employed [7]. This equation is originally used for carbon dioxide transportation, but in this study, it is also used for nitrogen transportation.

$$CAPEX_T = (A + B \times F) \tau L \quad (\text{A.25})$$

where F is the mass flow rate in million tons per year, L is the distance in km, τ is the terrain-related correction factor (1.0 for onshore flat terrain, 1.5 for mountainous terrain and 2.0 for offshore), and A and B are transportation parameters equal to 0.533 and 0.019, respectively.

Operating costs ($OPEX_T$) are considered as 4% of the capital costs [8].

$$OPEX_T = 0.04 \times CAPEX_T \quad (\text{A.26})$$

A.8. Cost of Injection well (CEPCI₂₀₀₇ = 525)

Additionally, in this study, the costs of injection wells are calculated using Eq. (A.27) [9]. Although this equation is originally presented for carbon dioxide injection, it can be reasonably used to estimate the costs associated with nitrogen injection.

$$CC_{InjWell} = N_{InjWell} \times 240,714 \times \exp(0.0008 \times D_{InjWell}) \quad (\text{A.27})$$

$$N_{InjWell} = Q_{N_2} / IC \quad (\text{A.28})$$

The depth of the injection wells, denoted as $D_{InjWell}$, is assumed to be 3,000 meters. The number of wells required for injection, represented as $N_{InjWell}$ is calculated using Eq. (A.28). In this

equation, Q_{Gas} represents the total flow rate of injected gas, while IC represents the injection capacity of a well.

A.9. Other Equations Required for Economic Evaluation

Chemical Engineering Plant Cost Index (CEPCI) in 2023, 2013 and 2007:

$CEPCI_{2023} = 797.9$, $CEPCI_{2013} = 567$, $CEPCI_{2007} = 525$

The total annual cost (TAC) include annualized capital expenditure ($CAPEX$) and operating expenditure ($OPEX$) (Eq. (A.29)).

$$TAC = OPEX + ACCR \times CAPEX \quad (\text{A.29})$$

Annual Capital Charge Ratio ($ACCR$) is calculated from Eq. (A.30).

$$ACCR = \frac{r(1+r)^y}{(1+r)^y - 1} \quad (\text{A.30})$$

$r = 0.15$ (Discount rate)

$y = 25$ years (Depreciation time)

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