Appendix A

Estimation of State Properties

A1: Simulation Model for AAVAR System

In order to determine the data that are not available from the online during the normal operation of the AAVAR plant at GNFC, Bharuch, Gujarat for the purpose of carrying out exergoeconomic optimization of the brine chilling unit using AAVAR system with steam from an independent boiler as heat energy source, a simulation model using EES solver is used. This Appendix A1 gives relations for the mass, energy and concentration balance for the components such as generator, rectifier of the AAVAR plant, energy balance for condenser, throttle valve and evaporator, effectiveness, mass and energy (enthalpy) balance for heat exchangers (RHX05 and RHX 06), energy balance for absorber and work done on absorber pump along with an expression for theoretical C.O.P.

**Generator**

\[ m_1 + m_4 = m_2 + m_3 \]  
\[ m_1 h_1 + m_4 h_4 - m_2 h_2 - m_3 h_3 + Q_g = 0 \]  
\[ m_1 x_1 + m_4 x_4 = m_2 x_2 + m_3 x_3 \]

(A1.1) \hspace{2cm} (A1.2) \hspace{2cm} (A1.3)

**Rectifier**

\[ m_3 + m_{18} = m_4 + m_5 \]  
\[ m_3 h_3 + m_{18} h_6 - m_4 h_4 - m_5 h_5 = 0 \]  
\[ m_3 x_3 + m_{18} x_6 = m_4 x_4 + m_5 x_5 \]  
\[ m_5 - m_{18} = m_{sup} + m_{10} \]

(A1.4) \hspace{2cm} (A1.5) \hspace{2cm} (A1.6) \hspace{2cm} (A1.7)
Condenser

\[ Q_c = m_z (h_5 - h_6) \] (A1.8)

Heat exchanger 06

\[ \chi_{06} = \frac{m_6 (h_6 - h_7)}{m_{10} (h_6 - h_{7m})} \] Where \( h_{7m} \) is minimum possible enthalpy. (A1.9)

\[ m_6 = m_{\text{evap}} + m_{10} \] (A1.10)

\[ \dot{m}_6 (h_6 - h_7) = \dot{m}_{10} (h_{11} - h_{12}) \] (A1.11)

Heat exchanger 05

\[ \chi_{05} = \frac{m_6 (h_7 - h_8)}{m_{\text{evap}} (h_7 - h_{8m})} \] Where \( h_{8m} \) is minimum possible enthalpy. (A1.12)

\[ \dot{m}_6 (h_7 - h_8) = \dot{m}_{\text{evap}} (h_{13} - h_{12}) \] (A1.13)

Throttle Valve

\[ h_8 = h_9 \] (A1.14)

Evaporator

\[ Q_e = m_{\text{evap}} (h_{12} - h_9) \] (A1.15)

Absorber

\[ \dot{m}_1 (h_1 - h_{15}) = \dot{m}_2 (h_2 - h_{16}) \] (A1.16)

\[ \dot{m}_2 h_7 + \dot{m}_{10} h_1 + \dot{m}_{\text{evap}} h_{13} - \dot{m}_1 h_{14} = Q_a = 0 \] (A1.17)

\[ W_p = \frac{v_{14} (P_G - P_p)}{\eta_p} \] (A1.18)
\[ W_p = m_i w_p \]  
\[ \varepsilon_{02} = \frac{(h_2 - h_{l_0})}{(h_2 - h_{l_{am}})} \]

Solving Eqs. A1.1 to A1.20, using EES solver, the properties at stations 1 to 18 can be estimated.

**A2: Energy Balance at Stations 21 to 34**

This part of the Appendix deals with energy balance for various components carried out to estimate properties at stations 21 to 34 that are not readily available through online data during the normal operation of the plant.

**A2.1 Energy Balance at Condenser**

Condenser condenses the ammonia vapour from rectifier and cools up to 40°C. From the system simulation, it is observed that the heat loss from the condenser is 3638 kW. The cooling water flow rate at condenser is 88.6 kg/sec with inlet temperature at station 23 is 33°C.

\[ Q_c = m_{cw_i} C_{cw} (T_{cw_i} - T_{cw_o}) \]  
(A2.1)

Considering the specific heat of cooling water \( C_{cw} = 4.187 \text{kJ/kgK} \), the outlet temperature of cooling water at condenser exit (station 24) is found to be 42.8°C.

**A2.2 Energy Balance at Absorber**

From the system simulation, it is observed that the heat rejected at absorber is 5405 kW. For absorber the cooling water flow rate is 125 kg/sec at 33°C at station 25.

\[ Q_u = m_{cw_i} C_{cw} (T_{cw_i} - T_{cw_o}) \]  
(A2.2)
From energy balance, it is observed that the temperature of cooling water at station 26 is 43.33°C

**A2.3 Energy Balance at Pre-cooler-1**

At Pre-cooler-1, liquid ammonia at 4 bar saturated enters at station 31. Its temperature is found to be -1.89°C. The exit temperature of ammonia at station 32 is measured to be 6.4°C. At given temperature and 4 bar pressure, the enthalpy of ammonia at stations 31 and 32 is found to be 191.3 and 1482 kJ/kg, respectively using EES solver. The brine enters the Pre-cooler-1 at 24.7°C and the specific heat of brine is found to be 3.08 using EES solver.

From energy balance across Pre-cooler-1

\[
m_{\text{brine}} C_{\text{brine}} (T_{29} - T_{30}) = m_{\text{ammonia,pc1}} (h_{32} - h_{31})
\] (A2.3)

Solving Eq.A2.3, the temperature of brine at station 30 is found to be 15.9°C.
Appendix B

Calculation for Exergy Parameters in Generator

This Appendix gives a sample calculation for the estimation of various exergy flow parameters such as fuel exergy, product exergy, exergy loss, exergy destruction, exergy destruction ratio, and exergetic efficiency in the generator. Appendix B1 gives the estimation of exergy at station 1. The sample calculation for various exergy related parameters in generator is given in Appendix B2. Similar calculations can be carried out for other components of the AAVAR system and pre-coolers 1 and 2.

B1 Total Exergy at Station 1

To calculate total exergy at state point 1, the values of mass flow rate of working fluid (strong solution), enthalpy and entropy at station 1 are taken from Table 5.1:

\[ m_1 = 18.28 \text{ kg/sec} \]
\[ h_1 = 292.80 \text{ kJ/kg} \]
\[ s_1 = 1.3760 \text{ kJ/kgK} \]

The enthalpy and entropy of the aqua ammonia solution at reference state (1.01 bar, 298.1 K) are found using EES and are estimated as follows:

\[ h_{01} = -67.73 \text{ kJ/kg} \]
\[ s_{01} = 0.3158 \text{ kJ/kgK} \]

Using the Eq.B1.1, the physical exergy at station 1 is calculated.

\[ E_{1PH} = m_1 \left[ (h_1 - h_{01}) - T_0 (s_1 - s_{01}) \right] \]  

\[ E_{1PH} = 18.28 \left[ ((292.80) - (-67.73)) - 298.15(1.3760 - 0.3158) \right] \]

\[ E_{1PH} = 811.9 \text{ kW} \]

The chemical exergy at station 1 can be calculated using Eq.B1.2

\[ E_{1CH} = m_1 \left[ \left( \frac{x_1}{M_{NH_3}} \right) e_{CH,NH_3}^0 + \left( \frac{1-x_1}{M_{H_2O}} \right) e_{CH,H_2O}^0 \right] \]  

From Table 5.1 and Table 5.2
\[ x_1 = 0.27 \]
\[ \dot{E}_{CH}^{1} = 18.28 \left[ \frac{0.27}{17} \right] 341250 + \left( 1 - \frac{0.27}{18} \right) 3120 \]
\[ \dot{E}_{CH}^{1} = 101407 \text{ kW} \]

Then the total exergy at station 1 is
\[ \dot{E}_1 = 811.9 + 101407 \]
\[ \dot{E}_1 = 102219 \text{ kW} \]

**B2 Estimation of Exergy Parameters at Generator**

**Fuel exergy,**
\[ \dot{E}_{F,G} = \dot{E}_{19} - \dot{E}_{20} \]
\[ \dot{E}_{F,G} = 39469 - 37830 \]
\[ \dot{E}_{F,G} = 1640 \text{ kW} \]

**Product exergy,**
\[ \dot{E}_{P,G} = \dot{E}_2 + \dot{E}_3 - \dot{E}_1 - \dot{E}_4 \]
\[ \dot{E}_{P,G} = 50806 + 53329 - 102220 - 352.4 \]
\[ \dot{E}_{P,G} = 1563 \text{ kW} \]

**Exergy loss** \[ \dot{E}_{L,G} = 0 \]

**Exergy destruction**
\[ \dot{E}_{D,G} = \dot{E}_{F,G} - \dot{E}_{P,G} - \dot{E}_{L,G} \]
\[ \dot{E}_{D,G} = 1640 - 1563 - 0 \]
\[ \dot{E}_{D,G} = 76.43 \text{ kW} \]
\[ Y_{D,G} = \frac{\dot{E}_{D,G}}{\dot{E}_{F,\text{tot}}} \]
Total Exergy Input

\[ \dot{E}_{\text{in, tot}} = \dot{E}_{F,G} + \dot{E}_{F,sp} + \dot{E}_{F,pc1} + \dot{E}_{F,pc2} \]

\[ \dot{E}_{\text{in, tot}} = 1639 + 38.59 + 325.9 + 608.7 \quad \text{kW} \]

First Destruction Ratio

\[ Y_{D,G} = \frac{\dot{E}_{D,G}}{\dot{E}_{F,\text{tot}}} \]

\[ Y_{D,G} = \frac{76.43}{2612.19} \]

\[ Y_{D,G} = 2.93\% \]

Second Destruction Ratio

\[ Y_{D,G}^* = \frac{\dot{E}_{D,G}}{\dot{E}_{D,\text{tot}}} \]

\[ \dot{E}_{D,\text{tot}} = 1818.59 \quad \text{kW} \]

\[ Y_{D,G}^* = \frac{76.43}{1818.59} \]

\[ Y_{D,G}^* = 4.20\% \]

Exergy Loss Ratio

\[ Y_{L,G} = \frac{\dot{E}_{L,G}}{\dot{E}_{F,\text{tot}}} \]

\[ Y_{L,G} = 0 \]

Exergetic Efficiency

\[ \varepsilon_G = \frac{\dot{E}_{P,G}}{\dot{E}_{F,G}} \]

\[ \varepsilon_G = \frac{1563}{1640} \]

\[ \varepsilon_G = 95.30\% \]
Appendix C

Estimation of Levelized O&M Cost for Generator

The method of estimation of levelized O&M cost for each components of AAVAR is adapted from Bejan et al. [155]. A sample calculation for the estimation of levelized O&M cost for the generator is given in this Appendix. The generator of the AAVAR plant is a 1-2 shell and tube heat exchanger. The technical specification of the generator is given below:

**Specification of HX**

- **Type**: 1-2 pass shell & tube heat exchanger
- **Flow arrangement**: Shell side strong solution & Tube side steam
- **Material**: Carbon Steel
- **No of tube**: 925
- **Length of HX**: 23 ft
- **Shell diameter**: 4.5 ft
- **Tube OD**: 1 in
- **HT area**: 517.4 m² (5570 ft²)
- **Cost of HX**: ₹1715000 for the year 1990 (from Fig. 5.3)
- **M & S cost index**: 915.1 (for the year 1990)
- **M & S cost index**: 1462.9 (for the second quarter of the year 2009)

Cost for the year 2009 = Cost for the year 1990 x (1462.9/915.1)

= ₹2741639

The total capital investment (TCI) for the generator is estimated using the estimated values of fixed capital investment (FCI) and other outlays. Based on the purchased equipment cost (PEC), all other cost components can be estimated as suggested by Bejan et al. [155]. Table 4.1 summarizes the various cost components of the generator used to estimate TCI.
Table C1 Total capital investment (TCI) from Table 4.1

<table>
<thead>
<tr>
<th>Fixed capital investment (FCI)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A  Direct cost (DC)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Onsite costs (ONSC)</strong></td>
<td></td>
</tr>
<tr>
<td>1 Purchased equipment cost (PEC)</td>
<td>2741639</td>
</tr>
<tr>
<td>2 installation cost (45% of PEC)</td>
<td>1233738</td>
</tr>
<tr>
<td>3 Piping (66 % of PEC)</td>
<td>1809482</td>
</tr>
<tr>
<td>4 Instrumentation and control (20 % of PEC)</td>
<td>548328</td>
</tr>
<tr>
<td>5 Electrical equipment and material (11% of PEC)</td>
<td>301580</td>
</tr>
<tr>
<td><strong>ONSC (1+2.3+4+5) = 6634766</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Off-site costs (OFSC)</strong></td>
<td></td>
</tr>
<tr>
<td>6 Land (10% of PEC)</td>
<td>274164</td>
</tr>
<tr>
<td>7 Civil, structural and architectural work (60% of PEC)</td>
<td>1644983</td>
</tr>
<tr>
<td>8 Service facilities (65 % of PEC)</td>
<td>1782065</td>
</tr>
<tr>
<td><strong>OFSC (6+7+8) = 3701213</strong></td>
<td></td>
</tr>
<tr>
<td><strong>DC (ONSC+ONFC) = 10335979</strong></td>
<td></td>
</tr>
<tr>
<td><strong>B  Indirect cost (IC)</strong></td>
<td></td>
</tr>
<tr>
<td>9 Engineering and supervision (30% of PEC)</td>
<td>822492</td>
</tr>
<tr>
<td>10 Construction cost with contractors profit (15% of DC)</td>
<td>1550397</td>
</tr>
<tr>
<td>11 Contingencies (20% of FCI)</td>
<td>1733027</td>
</tr>
<tr>
<td><strong>IC (9+10+11) = 4105916</strong></td>
<td></td>
</tr>
<tr>
<td><strong>FCI (DC+IC) = 14441895</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Other outlays</strong></td>
<td></td>
</tr>
<tr>
<td>12 Startup cost (10% of FCI)</td>
<td>1444189</td>
</tr>
<tr>
<td>13 Working capital (15% of TCI)</td>
<td>2851809</td>
</tr>
<tr>
<td>14 Cost of licensing</td>
<td>0</td>
</tr>
<tr>
<td>15 Allowance for funds used during construction (10% of PEC)</td>
<td>274164</td>
</tr>
<tr>
<td><strong>Other Outlays (12+13+14+15) = 4570162</strong></td>
<td></td>
</tr>
<tr>
<td><strong>TCI (FCI + Other Outlays) = 19012057</strong></td>
<td></td>
</tr>
</tbody>
</table>
**Capital Recovery Factor (β)**

It gives the amount to be collected at regular interval so that at the end of life of equipment, amount is ready to purchase new equipment.

\[
\beta = \left( \frac{i_{\text{eff}}(1+i_{\text{eff}})^n}{(1+i_{\text{eff}})^n-1} \right) \frac{1}{\tau} \ h^{-1}
\]

In this equation \( i_{\text{eff}} \) is the effective annual rate of return which is taken as 10% and \( N_y \) is the plant life taken as 30 years.

\[ \beta = 0.1061 \]

Operation and Maintenance (O&M) cost is assumed to be 1.092% of total investment cost as suggested by Tsatsaronis et al [114]. If the total working hours of the plant 8000 per year then cost flow rate associated with Operation and maintenance of generator will be

\[
\dot{Z}_G = \left[ \frac{\text{CRF} + \frac{1.092}{100}}{\tau} \right] \ast TCI_G
\]

Where \( TCI_G \) is the total capital investment 19010000 ₹ and \( \tau = 8000 \) hr

\[
\dot{Z}_G = \left[ \frac{0.1061 + \frac{1.092}{100}}{8000} \right] \ast 19010000
\]

\[ \dot{Z}_G = 278 \text{ ₹/hr} \]
Appendix D

Exergoeconomic Parameters for Generator

The Appendix deals with a sample calculation for the estimation of various exergoeconomic parameters for a typical component of AAVAR system like generator. Similar procedure of calculation may be followed for the estimation of the parameters for other components of the AAVAR plant. Firstly, the cost balance equation for the generator is written as given in Section D1. The exergoeconomic parameters such as relative cost difference and exergoeconomic factor are estimated using average product cost, exergy loss cost and exergy destruction cost and are described in Section D2.

D.1 Cost Balance Equation

For generator, exergetic cost associated with stream 1 and for 4 is the input cost whereas the cost associated with stream 2 and 3 is the output cost. If $c_1$ is the unit exergy cost in ₹/kJ and $E_1$ is the exergy flow in kW then $c_1 E_1$ will be the cost flow in ₹/sec. By cost flow balance

$$c_1 E_1 + c_4 E_4 - c_2 E_2 - c_3 E_3 + C_s + Z_g = 0$$

(D1.1)

All the terms in the above equation are in ₹/s.

For generator, flow 2 and 3 are the product. As per reference, unit exergy cost of each product is same. So net product [3-(1+4)] and [2-(1 + 4)]. So unit exergy cost is defined as $(cE_x)/E_x$

$$\frac{c_3 E_3 - (c_1 E_1 + c_4 E_4)}{E_3 - (E_1 + E_4)} = \frac{c_2 E_2 - (c_1 E_1 + c_4 E_4)}{E_2 - (E_1 + E_4)}$$

(D1.2)

Similar equations for other component are also developed. By solving all the equations using EES software, unit exergy cost of all the flows are calculated as shown in Table 5.8.
D.2 Exergoeconomic Parameters

To calculate fuel cost and product cost for generator, steam is the fuel so average steam cost $c_F$ is calculated as follows:

$$c_{F,G} = \frac{\dot{C}_{F,G}}{\dot{E}_{F,G}} \quad (D2.1)$$

$\dot{C}_{F,G}$ is the cost of steam taken from industry which is 0.9 ₹/kg. Mass flow rate of steam is 3.139 kg/s.

$$\dot{C}_{F,G} = 3.139 \times 0.9 \text{ (kg/sec} \times \text{ ₹/kg} = \text{ ₹/sec)}$$

$$= 2.83 \text{ ₹/sec}$$

Exergy of steam ($\dot{E}_{F,G} = \dot{E}_1 - \dot{E}_2$) where $\dot{E}_1$ exergy of inlet steam and $\dot{E}_2$ for exit from Table 5.3

$$\dot{E}_{F,G} = (39469 \text{ kW} - 37830 \text{ kW})$$

$$= 1640 \text{ kW}$$

$$c_{F,G} = 2.83/1640 \text{ (₹/kJ)}$$

$$= 1.724 \text{ ₹/MJ}$$

The product of generator is 2 and 3 where 1 and 4 are input. The cost of product from generator

$$\dot{C}_{P,G} = c_2 \dot{E}_2 + c_3 \dot{E}_3 - c_1 \dot{E}_1 - c_4 \dot{E}_4$$

Where $c_1, c_2, c_3, c_4$ are unit exergy costs and $\dot{E}_1, \dot{E}_2, \dot{E}_3, \dot{E}_4$ are exergy flows from Table 5.8

$$c_1 = 0.002949 \text{ ₹/kJ} \quad \dot{E}_1 = 102220 \text{ kW}$$

$$c_2 = 0.002934 \text{ ₹/kJ} \quad \dot{E}_2 = 50806 \text{ kW}$$

$$c_3 = 0.002936 \text{ ₹/kJ} \quad \dot{E}_3 = 53329 \text{ kW}$$

$$c_4 = 0.003655 \text{ ₹/kJ} \quad \dot{E}_4 = 352.4 \text{ kW}$$

So product $\dot{C}_{P,G} = 2.904 \text{ ₹/sec}$

The average product cost for generator is given by
\[ c_{P,G} = \frac{\dot{C}_{P,G}}{\dot{E}_{P,G}} \]  \hspace{1cm} (D2.2)

\( \dot{E}_{P,G} \) is the exergy of the product and given by

\[ \dot{E}_{P,G} = E_2 + E_3 - E_1 - E_4 \]

\( \dot{E}_{P,G} = 1563 \text{ kW} \)

\[ c_{P,G} = 2.904/1563 (\text{\textcurrency}/\text{sec})/(\text{kJ/sec}) = 1.86 \text{ \textcurrency/MJ} \]

The cost of exergy destruction for generator is given by

\[ \dot{C}_{D,G} = c_{F,G} \dot{E}_{D,G} \]

\( c_{F,G} = 1.724 \text{ \textcurrency/MJ} \) as above and \( \dot{E}_{D,G} = 76.43 \text{ kW} \) from Table 5.5. Then, cost of exergy destruction for generator

\[ \dot{C}_{D,G} = 1.724 \times 76.43 (\text{\textcurrency/MJ} \times \text{kJ/sec}) = 474.3 \text{ \textcurrency/hr} \]

Loss from the generator is zero. Loss is there only in condenser assembly so

\[ \dot{C}_{L,G} = c_{F,G} \dot{E}_{L,G}, \dot{C}_{L,G} = 0 \]

Relative cost difference, \( r \)

\[ r_G = \frac{c_{P,G} - c_{F,G}}{c_{F,G}} \]  \hspace{1cm} (D2.3)

\[ r_G = \frac{1.858 - 1.724}{1.724} \]

\[ r_G = 7.817\% \]

Exergoeconomic factor

\[ f_G = \frac{\dot{Z}_G}{\dot{Z}_G + (\dot{C}_{D,G} + \dot{C}_{L,G})} \]  \hspace{1cm} (D2.4)

\[ f_G = \frac{278}{278 + (474.3 + 0)} \]

\[ f_G = 36.96\% \]
Iterative Optimization Steps for Generator

An iterative procedure for optimization for each component of the AAVAR system is followed in a similar manner described in this Appendix. Following are the steps for iterative optimization for generator.

The factor $F$ is calculated using

$$ F_G = \left( \frac{(\beta + \gamma_G) B_G n_G}{\tau c_{F,G} E_{p,G}} \right)^{1/(n_G + 1)} $$  

(E.1)

For generator:

$\beta = 0.1061$, $\gamma_G = 1.092$, $B_G = 226231$ from Table 5.21,

$n_G = 0.048$, $\tau = 8000 \times 3600$ s, $c_{F,G} = 1.72/1000$ ₹/kJ from Table 5.9,

$m_G = 0.66$, $E_{p,G} = 1563$ kW for base case from Table 5.5.

Using Eq. E.1, $F_G$ is found to be 0.003.

Cost optimal exergetic efficiency

$$ \varepsilon_{G,OPT} = \frac{1}{1 + F_G} $$  

(E.2)

$$ \varepsilon_{G,OPT} = \frac{1}{1 + 0.003} $$

$$ \varepsilon_{G,OPT} = 0.997 $$

Relative cost difference

$$ r_{G,OPT} = \left( \frac{1 + n_G}{n_G} \right) F_G $$  

(E.3)

$$ r_{G,OPT} = \left( \frac{1 + 0.048}{0.048} \right) 0.003 $$
\[ r_G^{\text{OPT}} = 0.061 \]

**Exergoeconomic factor**

\[ f_G^{\text{OPT}} = \frac{1}{1 + n_G} \quad (E.4) \]

\[ f_G^{\text{OPT}} = \frac{1}{1 + 0.048} \]

\[ f_G^{\text{OPT}} = 0.954 \]

**Decision making parameters**

\[ \Delta \varepsilon_G = 100 \times \left( \varepsilon_G - \varepsilon_G^{\text{OPT}} \right) / \varepsilon_G^{\text{OPT}} \quad (E.5) \]

\[ \Delta \varepsilon_G = 100 \times (0.95 - 0.997) / 0.997 \]

\[ \Delta \varepsilon_G = -4.37 \]

\[ \Delta r_G = 100 \times \left( r_G - r_G^{\text{OPT}} \right) / r_G^{\text{OPT}} \quad (E.6) \]

\[ \Delta r_G = 100 \times (0.058 - 0.067) / 0.067 \]

\[ \Delta r_G = 28.32 \]
## Table F1: Variation of specific heat, enthalpy, absolute entropy and Gibbs function with temperature at 1 bar for various substances in unit kJ/kmol. [155]

<table>
<thead>
<tr>
<th>Substance</th>
<th>Formula</th>
<th>$c_p^o$</th>
<th>$h^o$</th>
<th>$s^o$</th>
<th>$g^o$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (graphite)</td>
<td>C(s)</td>
<td>8.53</td>
<td>0</td>
<td>5.740</td>
<td>-1711</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S(s)</td>
<td>22.77</td>
<td>0</td>
<td>32.058</td>
<td>-9558</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N$_2$(g)</td>
<td>28.49</td>
<td>0</td>
<td>191.610</td>
<td>-57128</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O$_2$(g)</td>
<td>28.92</td>
<td>0</td>
<td>205.146</td>
<td>-61164</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H$_2$(g)</td>
<td>29.13</td>
<td>0</td>
<td>130.679</td>
<td>-38961</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>CO(g)</td>
<td>28.54</td>
<td>-110528</td>
<td>197.648</td>
<td>-169457</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO$_2$(g)</td>
<td>35.91</td>
<td>-393521</td>
<td>213.794</td>
<td>-457264</td>
</tr>
<tr>
<td>Water</td>
<td>H$_2$O(g)</td>
<td>31.96</td>
<td>-241856</td>
<td>188.824</td>
<td>-298153</td>
</tr>
<tr>
<td>Water</td>
<td>H$_2$O(l)</td>
<td>75.79</td>
<td>-285829</td>
<td>69.948</td>
<td>-306685</td>
</tr>
<tr>
<td>Methane</td>
<td>CH$_4$(g)</td>
<td>35.05</td>
<td>-74872</td>
<td>186.251</td>
<td>-130403</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>SO$_2$(g)</td>
<td>35.59</td>
<td>-296833</td>
<td>284.094</td>
<td>-370803</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>H$_2$S(g)</td>
<td>33.06</td>
<td>-20501</td>
<td>205.757</td>
<td>-81847</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH$_3$(g)</td>
<td>35.59</td>
<td>-46111</td>
<td>192.451</td>
<td>-103491</td>
</tr>
</tbody>
</table>

2. For $298.15 < T \leq T_{max}$, $p_{ref} = 1$ bar, with $y = 10^{-3}T$

\[
\bar{c}_p^o = a + by + cy^2 + dy^2 \quad \text{(F1)}
\]

\[
\bar{h}^o = 10^3 \left[ H^* + ay + \frac{b}{2} y^2 - cy^{-1} + \frac{d}{3} y^3 \right] \quad \text{(F2)}
\]

\[
\bar{s}^o = S^* a \ln T + by - \frac{c}{2} y^{-2} + \frac{d}{2} y^2 \quad \text{(F3)}
\]

\[
\bar{g}^o = \bar{h}^o - T\bar{s}^o \quad \text{(F4)}
\]
<table>
<thead>
<tr>
<th>Substance</th>
<th>Formula</th>
<th>$H^+$</th>
<th>$S^+$</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (graphite)</td>
<td>C(s)</td>
<td>-2.101</td>
<td>-6.540</td>
<td>0.109</td>
<td>38.940</td>
<td>-0.146</td>
<td>-17.385</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S(s)</td>
<td>-5.242</td>
<td>-59.014</td>
<td>14.795</td>
<td>24.075</td>
<td>0.071</td>
<td>0</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>$N_2(g)$</td>
<td>-9.982</td>
<td>16.203</td>
<td>30.418</td>
<td>2.544</td>
<td>-0.238</td>
<td>0</td>
</tr>
<tr>
<td>Oxygen</td>
<td>$O_2(g)$</td>
<td>-9.589</td>
<td>36.116</td>
<td>29.154</td>
<td>6.477</td>
<td>-0.184</td>
<td>-1.017</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>$H_2(g)$</td>
<td>-7.823</td>
<td>-22.966</td>
<td>26.882</td>
<td>3.586</td>
<td>0.105</td>
<td>0</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>CO(g)</td>
<td>-120.809</td>
<td>18.937</td>
<td>30.962</td>
<td>2.439</td>
<td>-0.28</td>
<td>0</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO$_2(g)$</td>
<td>-413.886</td>
<td>-87.078</td>
<td>51.128</td>
<td>4.368</td>
<td>-1.469</td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td>$H_2O(g)$</td>
<td>-253.871</td>
<td>-11.750</td>
<td>34.376</td>
<td>7.841</td>
<td>-0.423</td>
<td>0</td>
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<tr>
<td>Water</td>
<td>$H_2O(l)$</td>
<td>-289.932</td>
<td>-67.147</td>
<td>20.355</td>
<td>109.198</td>
<td>2.033</td>
<td>0</td>
</tr>
<tr>
<td>Methane</td>
<td>CH$_4(g)$</td>
<td>-81.242</td>
<td>96.731</td>
<td>11.933</td>
<td>77.647</td>
<td>0.142</td>
<td>-18.414</td>
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<tr>
<td>Sulfur dioxide</td>
<td>SO$_2(g)$</td>
<td>-315.422</td>
<td>-43.725</td>
<td>49.936</td>
<td>4.766</td>
<td>-1.046</td>
<td>0</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>$H_2S(g)$</td>
<td>-32.887</td>
<td>1.142</td>
<td>34.911</td>
<td>10.686</td>
<td>-0.448</td>
<td>0</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH$_3(g)$</td>
<td>-60.244</td>
<td>-29.402</td>
<td>37.321</td>
<td>18.661</td>
<td>-0.649</td>
<td>0</td>
</tr>
</tbody>
</table>
Standard molar chemical exergy $e^{CH}$ (kJ/kmol) of various substances at 298.1 K and $p_0$ [155]

Chemical Exergy

The chemical exergy component is associated with the work obtainable in bringing a stream of matter from the state that is in thermal and mechanical equilibrium with the environment to a state that is in the most stable configuration in equilibrium with the environment. Thus it refers to the departure of chemical composition of the system to that of the environment. The chemical state of the environment composed of a suitably selected set of environmental substances. To exclude the possibility of developing work from interactions, physical or chemical, between parts of the environment, these reference substances need to be in mutual equilibrium. Since our natural environment is not in equilibrium, it is necessary to make compromise between the physical reality and the thermodynamic theory. Based on these compromises, alternative models for calculating chemical exergies are developed [154,160,161]. In these models, the term exergy reference environment is used to distinguish the thermodynamic concept from the natural environment. For simplicity, the chemical exergy based on standard chemical exergies determined relative to a standard environment is considered in present analysis.

Standard Chemical Exergy

Standard chemical exergies are based on standard environment that consists of a set of reference substances with standard concentrations of the natural environment. As explained in the above references, the reference substances are classified into three groups, gaseous components of the atmosphere, solid substances from lithosphere and ionic and non ionic substances from the oceans. Ahrendts [154] used restricted chemical equilibrium for nitric acid and nitrates, and unrestricted thermodynamic equilibrium for all other chemical components of the atmosphere, the oceans and a portion of the lithosphere to determine the standard chemical exergy reference environments. This model attempts to satisfy both the thermodynamic equilibrium requirements and the
chemical composition of the natural environment for the gas phase. Szargut et al. [161] presented a different approach where a reference substance is selected for each chemical element among the abundantly available natural environment substances that contains the elements being considered, even though the substance are not in complete stable equilibrium. The basis of this approach is that the substances found abundantly in nature have little economic value. In this approach, though the chemical composition of the exergy reference environment is closer to the composition of natural environment, the equilibrium requirement is not generally satisfied. In this work, the approach suggested by Szargut [161] is considered for analysis. Using this approach, the method to calculate standard chemical exergy and table of standard chemical exergies of substances is presented by Kotas [118].

Table G.1 gives the standard chemical exergy of some well known substances.
<table>
<thead>
<tr>
<th>Substance</th>
<th>Formula</th>
<th>Model I</th>
<th>Model II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>N₂(g)</td>
<td>639</td>
<td>720</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂(g)</td>
<td>3951</td>
<td>3970</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO₂(g)</td>
<td>14176</td>
<td>19870</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O(g)</td>
<td>8636</td>
<td>9500</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O(l)</td>
<td>45</td>
<td>900</td>
</tr>
<tr>
<td>Carbon(graphite)</td>
<td>C(s)</td>
<td>404589</td>
<td>410260</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H₂(g)</td>
<td>235249</td>
<td>236100</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S(s)</td>
<td>598158</td>
<td>609600</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>CO(g)</td>
<td>269412</td>
<td>275100</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>SO₂(g)</td>
<td>301939</td>
<td>313400</td>
</tr>
<tr>
<td>Nitrogen monoxide</td>
<td>NO(g)</td>
<td>88851</td>
<td>88900</td>
</tr>
<tr>
<td>Nitrogen dioxide</td>
<td>NO₂(g)</td>
<td>55565</td>
<td>55600</td>
</tr>
<tr>
<td>Hydrogen peroxide</td>
<td>H₂O₂(g)</td>
<td>133587</td>
<td>-</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>H₂S</td>
<td>799890</td>
<td>812000</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH₃(g)</td>
<td>336684</td>
<td>337900</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O(g)</td>
<td>231968</td>
<td>233700</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H(g)</td>
<td>320822</td>
<td>331300</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N(g)</td>
<td>453821</td>
<td>-</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄(g)</td>
<td>824348</td>
<td>831650</td>
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<tr>
<td>Acetylene</td>
<td>C₂H₂(g)</td>
<td>-</td>
<td>1265800</td>
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<tr>
<td>Ethylene</td>
<td>C₂H₄(g)</td>
<td>-</td>
<td>1361100</td>
</tr>
<tr>
<td>Ethane</td>
<td>C₂H₆(g)</td>
<td>1482033</td>
<td>1495840</td>
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<tr>
<td>Propylene</td>
<td>C₃H₆(g)</td>
<td>-</td>
<td>2003900</td>
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<tr>
<td>Propane</td>
<td>C₃H₈(g)</td>
<td>-</td>
<td>2154000</td>
</tr>
<tr>
<td>n-Butane</td>
<td>C₄H₁₀(g)</td>
<td>-</td>
<td>2805800</td>
</tr>
<tr>
<td>n-Pentane</td>
<td>C₅H₁₂(g)</td>
<td>-</td>
<td>3463300</td>
</tr>
<tr>
<td>Benzene</td>
<td>C₆H₆(g)</td>
<td>-</td>
<td>3303600</td>
</tr>
<tr>
<td>Octane</td>
<td>C₈H₁₈(l)</td>
<td>-</td>
<td>5413100</td>
</tr>
<tr>
<td>Methanol</td>
<td>CH₃OH(g)</td>
<td>715069</td>
<td>722300</td>
</tr>
<tr>
<td>Methanol</td>
<td>CH₃OH(l)</td>
<td>710747</td>
<td>718000</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>C₂H₅OH(g)</td>
<td>1348328</td>
<td>1363900</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>C₂H₅OH(l)</td>
<td>1342086</td>
<td>1375700</td>
</tr>
</tbody>
</table>
Appendix-H

Purchase Equipment Cost (PEC)

The procedure for the estimation of PEC for the various components of gas turbine and steam turbine power plant are given in this Appendix. Section H.1 [117] gives the necessary relation pertaining to components of gas turbine plant while section H.2 [139] gives that of steam turbine power plant.

Table H.1 Gas turbine power plant

<table>
<thead>
<tr>
<th>Component</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>$PEC_{AC} = \left( \frac{C_{11} m_a}{C_{12} - \eta_{AC}} \right) \left( \frac{P_2}{P_1} \right) \ln \left( \frac{P_2}{P_1} \right)$</td>
</tr>
<tr>
<td></td>
<td>$C_{11} = 39.5$/\text{(kg/sec)}, \quad C_{12} = 0.9$</td>
</tr>
<tr>
<td>Combustion chamber</td>
<td>$PEC_{CC} = \left( \frac{C_{21} m_a}{C_{22} P_4 - \frac{P_4}{P_3}} \right) \left[ 1 + \exp \left( C_{23} T_4 - C_{24} \right) \right]$</td>
</tr>
<tr>
<td></td>
<td>$C_{21} = 25.6$/\text{(kg/sec)}, \quad C_{22} = 0.995$</td>
</tr>
<tr>
<td></td>
<td>$C_{23} = 0.018\text{(K)}^{-1}, \quad C_{24} = 26.4$</td>
</tr>
<tr>
<td>Gas Turbine</td>
<td>$PEC_{GT} = \left( \frac{C_{31} m_g}{C_{32} - \eta_{GT}} \right) \ln \left( \frac{P_2}{P_3} \right) \left[ 1 + \exp \left( C_{33} T_4 - C_{34} \right) \right]$</td>
</tr>
<tr>
<td></td>
<td>$C_{31} = 266.3$/\text{(kg/sec)}, \quad C_{32} = 0.92$</td>
</tr>
<tr>
<td></td>
<td>$C_{33} = 0.036\text{(K)}^{-1}, \quad C_{34} = 54.4$</td>
</tr>
<tr>
<td>Air preheater</td>
<td>$PEC_{aph} = C_{41} \left( \frac{m_g (h_g - h_h)}{U \Delta T_{lm,aph}} \right)^{0.6}$</td>
</tr>
<tr>
<td></td>
<td>$C_{41} = 2292 $/\text{(m}^2\text{)}^{-1}, \quad U=18 \text{ kW/m}^2\text{K}$</td>
</tr>
<tr>
<td>HRSG</td>
<td>$PEC_{hrsg} = C_{51} \left[ \left( \frac{\dot{Q}<em>{ev}}{\Delta T</em>{lm,ec}} \right)^{0.8} + \left( \frac{\dot{Q}<em>{ev}}{\Delta T</em>{lm,ec}} \right)^{0.8} \right] + C_{52} m_{st} + C_{53} m_g^{1.2}$</td>
</tr>
<tr>
<td></td>
<td>$C_{51} = 3650 $/\text{(kW/K)}^{0.8}, \quad C_{52} = 11820 $/\text{(kg/sec)}$</td>
</tr>
<tr>
<td></td>
<td>$C_{53} = 658 $/\text{(kg/sec)}^{1.2}$</td>
</tr>
</tbody>
</table>
Table H.2 Steam Turbine Power Plant

\[
I_{BL} = 740(h_s)^{0.8} \exp\left(\frac{P - 2}{446}\right) \exp\left(\frac{T - 350}{446}\right)
\]

Boiler

- \( h_s \): enthalpy transferred to steam in kW
- \( P \): boiler pressure in MPa
- \( T \): boiler temperature in °C

\[
I_{ST} = 6000 (E_p)^{0.7}
\]

Steam Turbine

- \( E_p \): power generated in kW

\[
I_{COND} = 1773(m_s)
\]

Condenser

- \( m_s \): steam flow rate in kg/sec

\[
I_{PUMP} = 3540(W_p)^{0.71}
\]

Pump

- \( W_p \): shaft work in kW
Steam Pipe Cost

It is decided to tap steam at 17 bar from steam turbine and to use as a fuel in AAVAR system. For this, the cast steel pipe line of 6 inch size is designed for 17 kg/cm², 340°C and 12.3 tonne/hr and selected pipe material is A106 Grade-B Seamless Schedule 40 IBR (Carbon steel). The cost of cast steel pipe is 35000 ₹/tonne.

For selected pipe, following dimensions are considered.

\[D_o = 6.63 \text{ inch}\]
\[D_i = 6.07 \text{ inch}\]
\[L = 1 \text{ km}\]

Volume of pipe line per meter length

\[V = \frac{\pi}{4} \left(D_o^2 - D_i^2\right) \times 1\]
\[V = 0.0036 \text{ m}^3\]

Density of pipe material
\[\rho = 7850 \text{ kg/m}^3\]

Mass of pipe per meter length
\[m = \rho \times V\]
\[m = 28.3 \text{ kg/m}\]

Cost of pipe per meter length
\[= m \times 35\]
\[= 990 \text{ ₹/meter}\]
Including transportation charges
Cost=1008 ₹/meter
PUBLICATIONS FROM THE THESIS

International Journal


Presented and Published in International Conference


This is to acknowledge my indebtedness to my guide, **Prof P Prabhakaran**, Professor, Department of Mechanical Engineering, Faculty of Tech. & Engg., The M S University of Baroda, Vadodara, for his guidance and suggestions for preparing this PhD thesis. His towering presence instilled in me the craving to work harder and complete this daunting task timely with sufficient degree of independent study. I am highly thankful for his edifying guidance and encouragement provided to me throughout the completion of my PhD work that enhanced the confidence in me. The keen and personal efforts of the guide made the long process of this work a very pleasant end.

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Last but not the least I am thankful to the Almighty who gave me the strength and health for completing the work.

(V K Matawala)