Chapter 5

Exergoeconomic Optimization of Existing System

The unified scheme of exergoeconomic optimization using a combination of TEO method, suggested by Tsatsaronis and an exergy analysis using EGM and EDM approach is given in chapter 4. A flow chart depicting the various steps involved in the unified scheme is also given. This scheme is now employed to carry out the Exergoeconomic Optimization of an industrial AAVAR system in which economy with existing heat source is analyzed.

5.1 Exergy Analysis

For the case of an industrial 800 TR AAVAR system used for brine chilling in which the steam generated in an independent boiler (boiler No. 38/02) is used as heat source (fuel), the cooling cost for the cooling generated at the evaporator of the AAVAR system is optimized and presented in this chapter. The following are the various steps involved in the cooling cost optimization.

5.1.1 System Simulation

Using the governing equations for the processes undergone in each component considering mass, energy and concentration balances [148,149,150], AAVAR system simulation is carried out with the help of EES software [151]. For estimating the properties such as enthalpy, entropy and specific volume of aqua ammonia solution circulated in the condensing unit, the inbuilt subroutine of EES software is used. They are then compared with the properties provided by Ziegler et al. [152] and Patek et al. [153].

The simulation is necessary as data needed at number of stations are not available online during normal operation of the plant. This may be due to the reason that they are not critical for the day to day monitoring and operation of the plant. The simulation model along with the fundamental equation is given in Appendix A1. For the simulation of the AAVAR system, following assumptions are taken.

1. The system is in a steady state.
2. The temperatures of the component in the generator, condenser, evaporator and absorber are constant and uniform.
3. The generator and rectifier pressures are equal.
4. The pressure losses in the pipe between the rectifier and the condenser, and between the RHX 05 and absorber are expressed as $\Delta p/p_{out}$ = 0.05 and $\Delta p/p_{out}$ = 0.075, respectively [90].
5. The condenser pressure and evaporator pressures are the equilibrium pressures corresponding to the temperature and concentration in the condenser and in the evaporator, respectively.
6. The refrigerant vapour concentration at station 3 is 0.99 and the temperature at station 4 is 100°C.

As mentioned earlier, it should be noted that the online data available from the AAVAR plant (refer Table 3.1) is not complete for the purpose of exergy analysis due to the reason that the data needed for the smooth functioning and monitoring of the plant operation does not need all of them. Hence few data not available at certain stations are to be worked out which one cannot measure due to obvious reasons of the impossibility of introducing measurement systems in the plant. Therefore, a system simulation should be carried out to generate the missing data. Table 5.1 gives the data not available through online measurements generated through simulation using EES solver and already available data from the online monitoring. Table 5.1 also gives the estimated values of enthalpy and entropy at stations 1 to 18 using the solver.

The AAVAR system uses steam generated in the independent boiler No. 38/02 as heat source. The boiler supplies saturated steam at 15 bar at a flow rate of 3.14 kg/sec.

The properties of steam at given pressure and corresponding saturation temperature are estimated using inbuilt subroutine of EES software at stations 19 and 20.

Table 5.1 Generated Online Data for AAVAR System

Stations	mass flow rate kg/sec	Pressure. bar	Temperature. °C	NH_3 Concentration % wt	Enthalpy kJ/kg	Entropy kJ/kgK
1	18.28	18.90	107.70	0.270	292.80	1.3760
2	15.70	18.90	140.00	0.150	497.30	1.7800
3	2.62	18.90	140.00	0.990*	1576.00	4.8730
4	0.04	18.90	100.00*	0.448	216.70	1.2430
5	3.17	18.90	60.00	0.998	1338.00	4.2330
6	2.59	18	40.00	0.998	189.30	0.6580
7	2.59	18	35.87	0.998	168.90	0.5924
8	2.59	18	11.65	0.998	52.97	0.2018
9	2.59	1.90	-19.90	0.998	52.97	0.2415
10	0.24	1.90	-20.00	0.970	-113.60	-0.3284
11	0.24	1.90	-19.22	0.970	111.00	0.5523
12	2.35	1.90	-20.00	1.000	1243.00	4.9140
13	2.35	1.90	35.16	1.000	1371.00	5.3710
14	18.28	1.77	40.00	0.270	-3.58	0.5254
15	18.28	18.90	40.14	0.270	-1.50	0.5261
16	15.70	18.90	60.58	0.150	154.50	0.8593
17	15.70	1.77	60.90	0.150	154.50	0.8648
18	0.58	18	40.00	0.998	189.30	0.6580

(* Assumed data)

At evaporator, the cooling generated is utilized in chilling the brine. The temperature of brine at inlet and exit are measured online. The properties of brine at stations 21 and 22 are estimated with the help of EES software

Condenser and absorber are supplied cooling water from common cooling tower No. 34/02 at 33°C. The cooling water flow rate through condenser is 317 m^3 /hr. (The equivalent mass flow rate of cooling water through condenser is 88.06 kg/sec). After absorbing the heat from ammonia vapour in the condenser, the cooling water is heated to

42.8°C and returns to cooling tower. The volume flow rate of cooling water through absorber is 453 m^3/hr. (The equivalent mass flow rate is 125 kg/sec). In the absorber, the ammonia vapour from evaporator and weak solution from generator are mixed. The mixing process is exothermic and the released heat is absorbed by cooling water in the absorber. The cooling water at the absorber exit is heated to 43.30°C and returns to cooling tower. The temperature of cooling water at condenser and absorber exit is calculated from energy balance as explained in Appendix A2. Considering the cooling water and brine at atmospheric pressure, the properties of cooling water (stations 23 to 26) are estimated using EES software and given in Table 5.2.

After estimating the properties at various stations of AAVAR system, properties of working fluids at various stations of pre-cooler-1 and pre-cooler-2 are estimated. Pre-cooler-1 cools the incoming brine at a flow rate of 125 kg/sec from the process plant and enters the evaporator of AAVAR at a temperature of 24.7°C. The fertilizer industry is manufacturing many products. Ammonia, one among them, is used as raw material and is manufactured at two pressure levels viz. 4 bar and 2.3 bar in different manufacturing plants in saturated liquid form. Saturated liquid ammonia at 4 bar enters the shell side of the pre-cooler-1 at a steady rate of 9.2 ton per hour and evaporates while absorbing latent heat from the brine. The exit temperature of brine is estimated through energy balance across Pre-cooler-1 and found to be 15.9°C.The ammonia leaving the pre-cooler-1 is heated up to 6.4°C and consumed in the fertilizer plant.

The brine from pre-cooler-1 then enters the tube side of pre-cooler-2, which is a shell and tube type heat exchanger, at 15.9°C. Saturated ammonia at 2.3 bar at the steady rate of 10.3 ton per hour enters the shell side and evaporates while absorbing latent heat from the brine and cools the brine up to 5.4°C. During the heat exchange process, the ammonia at exit is heated up to 12.5°C and consumed in the fertilizer plant. The properties of ammonia at stations 31 to 34 are estimated at given temperature and pressure using inbuilt subroutine of EES software and given in Table 5.2. The temperature of brine at exit of Pre-cooler-1 is estimated through energy balance at Pre-cooler-1 as explained in Appendix A2 and its properties at station 30 is estimated using EES software and given in Table 5.2.

Table 5.2 Generated Online Data for AAVAR System and Pre-coolers

Stations	mass flow rate kg/sec	Pressure. bar	Temperature. °C	NH_3 Concen tration % wt	Enthalpy kJ/kg	Entropy kJ/kgK
19	3.14	15.00	198.30	0	2791.00	6.4440
20	3.14	15.00	198.30	0	1370.00	3.4300
21	125.00	1.01	5.40	0	16.55	0.0600
22	125.00	1.01	-1.70	0	-5.19	-0.0191
23	88.06	1.01	33.00	0	138.30	0.4777
24	88.06	1.01	44.80	0	171.80	0.5856
25	125.00	1.01	33.00	0	138.30	0.4777
26	125.00	1.01	43.30	0	171.80	0.5856
27	---	---	---	---	---	---
28	---	---	---	---	---	---
29	125.00	1.01	24.70	0	76.36	0.2677
30	125.00	1.01	15.90	0	48.97	0.1743
31	2.56	4.00	-1.89	---	191.30	0.9681
32	2.56	4.00	6.40	---	1482.00	5.7240
33	2.85	2.3	-15.62	---	128.40	0.7312
34	2.85	2.3	12.50	---	1510.00	6.0830

5.1.2 Exergy Destruction Method (EDM) of Exergy Analysis

After estimation of properties at all the stations 1 to 34, the exergy flow at all the stations is calculated. Considering the system at rest with respect to environment, the total exergy becomes the sum of physical and chemical exergy. The physical exergy component associated with the work obtainable in bringing a matter from its initial state to a state that is in thermal and mechanical equilibrium with the environment is given by the Eq. 4.2. Chemical exergy associated with the fluid is calculated using the following:

$$\dot{E}_i^{CH} = \dot{m}_i \left[\left(\frac{x_i}{M_{NH_3}} \right) e^0_{CH,NH_3} + \left(\frac{1-x_i}{M_{H_2O}} \right) e^0_{CH,H_2O} \right] \tag{5.1}$$

Where $e^0_{CH,NH_3} = 341250$ kJ/kmol and $e^0_{CH,H_2O} = 3120$ kJ/kmol are the standard chemical exergy of ammonia and water, respectively and is given by Kotas [118]. $M_{NH_3} = 17$ kg/kmol and $M_{H_2O} = 18$ kg/kmol are molecular weight of ammonia and water, respectively. The exergy flow in terms of physical, chemical and total exergy at all stations is estimated using Eqs. 4.2, 5.1 and 4.3, respectively and is given in Table 5.3. For this purpose, the enthalpy and entropy available at thirty four stations in brine chilling unit estimated from the online data and given in Table 5.1 and Table 5.2 are used. A sample calculation is given in Appendix B1.

5.1.2.1 Definition of Fuel, Product and Loss for Various Processes

The calculated values of physical, chemical and total exergy given in Table 5.3 can now be used to define fuel, product and loss for the purpose of exergoeconomic analysis. Based on the definition of fuel, product and loss given in Section 4.1.1, the estimated values of exergy can be translated in to the fuel, the product and the loss for each component of the AAVAR system. Following few paragraphs are devoted for the definition with respect to each component of AAVAR.

Generator

The function of generator in AAVAR system is to separate ammonia vapour from the strong aqua ammonia solution by heating. This is accomplished by using steam generated in an independent boiler. In the generator, therefore, by adding heat energy to the strong aqua ammonia solution, ammonia vapour is separated from the solution to the greatest extent possible. The separated water along with residual ammonia as mixture flows back to absorber. As per exergy analysis point of view, the transfer of steam in to the generator is interpreted as transfer of exergy from steam. Thus the exergy gained by the ammonia vapour separated and the exergy of the leaving stream of aqua ammonia weak solution becomes the product for the generator.

Rectifier

In the rectifier, the exergy of reflux is used to increase the exergy of ammonia separated in the form of vapour (refrigerant) in the generator by condensing the water vapour as a carryover by evaporating some portion of reflux. So the concentration of the ammonia vapour can be increased by vaporizing liquid water droplets present in ammonia vapour. Therefore, the decrease in the exergy of reflux is the fuel and rise in the exergy of ammonia vapour is the product for rectifier.

Table 5.3 State Properties for AAVAR System

Stations	Mass flow rate kg/sec	Pres-sure. bar	Temp. °C	NH_3 Concentration % wt	Specific Enthalpy kJ/kg	Specific Entropy kJ/kgK	Chemical Exergy kW	Physical Exergy kW	Total Exergy kW
1	18.28	18.70	107.70	0.270	292.80	1.3760	101407	811.90	102219
2	15.70	18.70	140.00	0.150	497.30	1.7800	49574	1232.00	50806
3	2.62	18.70	140.00	0.990*	1576.00	4.8730	52180	1142.00	53321
4	0.04	18.70	100.00*	0.448	216.70	1.2430	346.9	1.89	348.7
5	3.17	18.70	60.00	0.998	1338.00	4.2330	63470	1257.00	64727
6	2.59	17.81	40.00	0.998	189.30	0.6580	51833	812.80	52645
7	2.59	17.81	35.87	0.998	168.90	0.5924	51833	810.60	52643
8	2.59	17.81	11.65	0.998	52.97	0.2018	51833	811.90	52645
9	2.59	1.90	-19.90	0.998	52.97	0.2415	51833	781.30	52614
10	0.24	1.90	-20.00	0.970	-113.60	-0.3284	4581	70.74	4652
11	0.24	1.90	-19.22	0.970	111.00	0.5523	4581	61.79	4643
12	2.35	1.90	-20.00	1.000	1243.00	4.9140	47214	229.10	47443
13	2.35	1.90	35.16	1.000	1371.00	5.3710	47121	208.50	47329
14	18.28	1.77	40.00	0.270	-3.58	0.5254	101407	29.90	101437
15	18.28	18.70	40.14	0.270	-1.50	0.5261	101407	64.65	101471
16	15.7	18.70	60.58	0.150	154.50	0.8593	49574	158.60	49733
17	15.7	1.77	60.90	0.150	154.50	0.8648	49574	132.90	49707
18	0.58	18.70	40.00	0.998	189.30	0.6580	11637	182.50	11820
19	3.14	15.00	198.30	0	2791.00	6.4440	36725	2744.00	39469
20	3.14	15.00	198.30	0	1370.00	3.4300	36725	1105.00	37830
21	125.00	1.01	5.40	0	16.55	0.0600	1.50E+06	283.50	1.50E+06
22	125.00	1.01	-1.70	0	-5.19	-0.0191	1.50E+06	510.40	1.50E+06
23	88.06	1.01	33.00	0	138.30	0.4777	274733	38.74	274772
24	88.06	1.01	44.80	0	171.80	0.5856	274733	152.50	274886
25	125.00	1.01	33.00	0	138.30	0.4777	392600	55.36	392655
26	125.00	1.01	43.30	0	171.80	0.5856	392600	217.90	392818
27	---	---	---	---	---	---	---	---	42.38
28	---	---	---	---	---	---	---	---	38.14
29	125.00	1.01	24.70	0	76.36	0.2677	1.50E+06	0.06	1.50E+06
30	125.00	1.01	15.90	0	48.97	0.1743	1.50E+06	55.33	1.50E+06
31	2.56	4.00	-1.89	---	191.30	0.9681	51388	829.5	52218
32	2.56	4.00	6.40	---	1482.00	5.7240	51388	503.7	51892
33	2.85	2.3	-15.62	---	128.40	0.7312	57210	945.5	58155
34	2.85	2.3	12.50	---	1510.00	6.0830	57210	336.8	57546

Heat Exchangers – SHX, RHX05 and RHX06

In the solution heat exchanger (SHX), the exergy of the strong aqua ammonia solution flowing to the generator is increased by transferring the exergy of weak aqua ammonia solution from the generator while flowing to the absorber. In the ammonia heat exchanger (RHX 05), the liquid ammonia leaving the condenser is sub cooled by the vapour leaving the evaporator and in (RHX 06) the liquid ammonia from the condenser is sub cooled by the separated aqua ammonia weak solution in the evaporator.

Absorber

Ammonia vapour (refrigerant) from the evaporator and the weak aqua ammonia solution (absorber) from generator are mixed in the absorber. In fact, the absorber acts as an absorber for ammonia vapour (refrigerant) in to liquid water and forms a strong aqua ammonia solution. The process of ammonia absorption is an exothermic reaction and heat released is dissipated in the cooling water circulated in cooling coils. Weak solution from generator and ammonia vapour from evaporator are considered as a fuel. The strong aqua ammonia solution flowing to the generator is considered as a product. The dissipated heat energy in to the cooling water is considered as loss. The exergy of the strong solution leaving the absorber is increased in the solution pump by transferring the exergy of the external work provided to the pump.

Condenser-Evaporator

The evaporator increases the exergy of the chilled brine by transferring the exergy from the refrigerant. In case of heat dissipative components like condenser, throttling valve, pressure reducing valve, the product cannot be defined. Therefore evaporator and condenser together are considered as single virtual component as suggested by Sahoo et al. [90]. Heat rejected in condenser in cooling water is considered as exergy loss. For expansion valve and pressure reducing valve, fuel and product cannot be decided but only exergy destruction can be calculated which is added in the exergy destruction of the overall system.

Pre-cooler-1 and Pre-cooler-2

As mentioned earlier, saturated liquid ammonia at two different pressure levels is used for pre-cooling the brine before entering the ammonia (refrigerant) evaporator. The latent heat of evaporation and heat required for superheating is absorbed from the brine coming from the process plant for brine chilling. Therefore, the change in exergy of the evaporating ammonia is considered as a fuel and the chilling of the brine is the product in both the pre-coolers.

Fig. 5.1 illustrates the schematic of the sub systems of AAVAR system for the purpose of exergoeconomic analysis and optimization. It should be noted that, conventionally, rectifier-generator assembly is a part of the condensing unit. Evaporator is one of the other main components along with condensing unit in the plant for conventional thermodynamic analysis. Since the product cannot be defined for condenser as mentioned earlier, the evaporator and condenser together are considered as a single virtual component for the purpose of exergoeconomic analysis. Table 5.4 gives the defined fuel, product and loss for each of the ten productive components considered for analysis, namely, generator, rectifier, condenser-evaporator assembly, solution pump, SHX, RHX 05, RHX 06, absorber, pre-cooler-1 and pre-cooler-2.

Table 5.4 Definition of Fuel, Product and Loss for Components of AAVAR System

Component	Fuel ($\dot{E}_F$)	Product($\dot{E}_P$)	Loss($\dot{E}_L$)
Generator	$\dot{E}_{19}-\dot{E}_{20}$	$\dot{E}_2+\dot{E}_3-\dot{E}_1-\dot{E}_4$	----
Rectifier	$\dot{E}_{18}-\dot{E}_4$	$\dot{E}_5-\dot{E}_3$	----
Condenser Evaporator. Assembly	$\dot{E}_5-\dot{E}_{18}-\dot{E}_6+\dot{E}_9-\dot{E}_{12}-\dot{E}_{10}$	$\dot{E}_{22}-\dot{E}_{21}$	$\dot{E}_{24}-\dot{E}_{23}$
SHX	$\dot{E}_2-\dot{E}_{16}$	$\dot{E}_1-\dot{E}_{15}$	----
RHX 05	$\dot{E}_{12}-\dot{E}_{13}$	$\dot{E}_8-\dot{E}_7$	----
RHX 06	$\dot{E}_{10}-\dot{E}_{11}$	$\dot{E}_6-\dot{E}_7$	----
Solution Pump	$\dot{W}_p$	$\dot{E}_{15}-\dot{E}_{14}$	----
Absorber	$\dot{E}_{11}+\dot{E}_{13}+\dot{E}_{17}$	$\dot{E}_{14}$	$\dot{E}_{26}-\dot{E}_{25}$
Pre-cooler-1	$\dot{E}_{31}-\dot{E}_{32}$	$\dot{E}_{30}-\dot{E}_{29}$	----
Pre-cooler-2	$\dot{E}_{33}-\dot{E}_{34}$	$\dot{E}_{21}-\dot{E}_{30}$	----
Overall System	$\dot{F}_G+\dot{F}_{sp}+\dot{F}_{pc1}+\dot{F}_{pc2}$	$\dot{P}_{CE}+\dot{P}_{pc1}+\dot{P}_{pc2}$	$\dot{E}_{24}-\dot{E}_{23}+\dot{E}_{26}-\dot{E}_{25}$

5.1.2.2 Exergetic Destruction, Loss and Efficiency

The exergy analysis of AAVAR system includes the calculations for the exergy destruction, $\dot{E}_D$, exergy destruction ratio, Y_D, the exergy loss, Y_L, the exergy loss ratio,

Y_D^* and the exergetic efficiency, ε for each productive components and the overall system and is carried out using Eqs. 4.4 to 4.8. Appendix B2 gives a sample calculation of the same. The calculated values of exergetic destruction, exergy loss and exergetic efficiency are listed for each productive components of AAVAR system in Table 5.5. The rate of exergy destruction in each of the components is pictorially represented in Fig. 5.2.

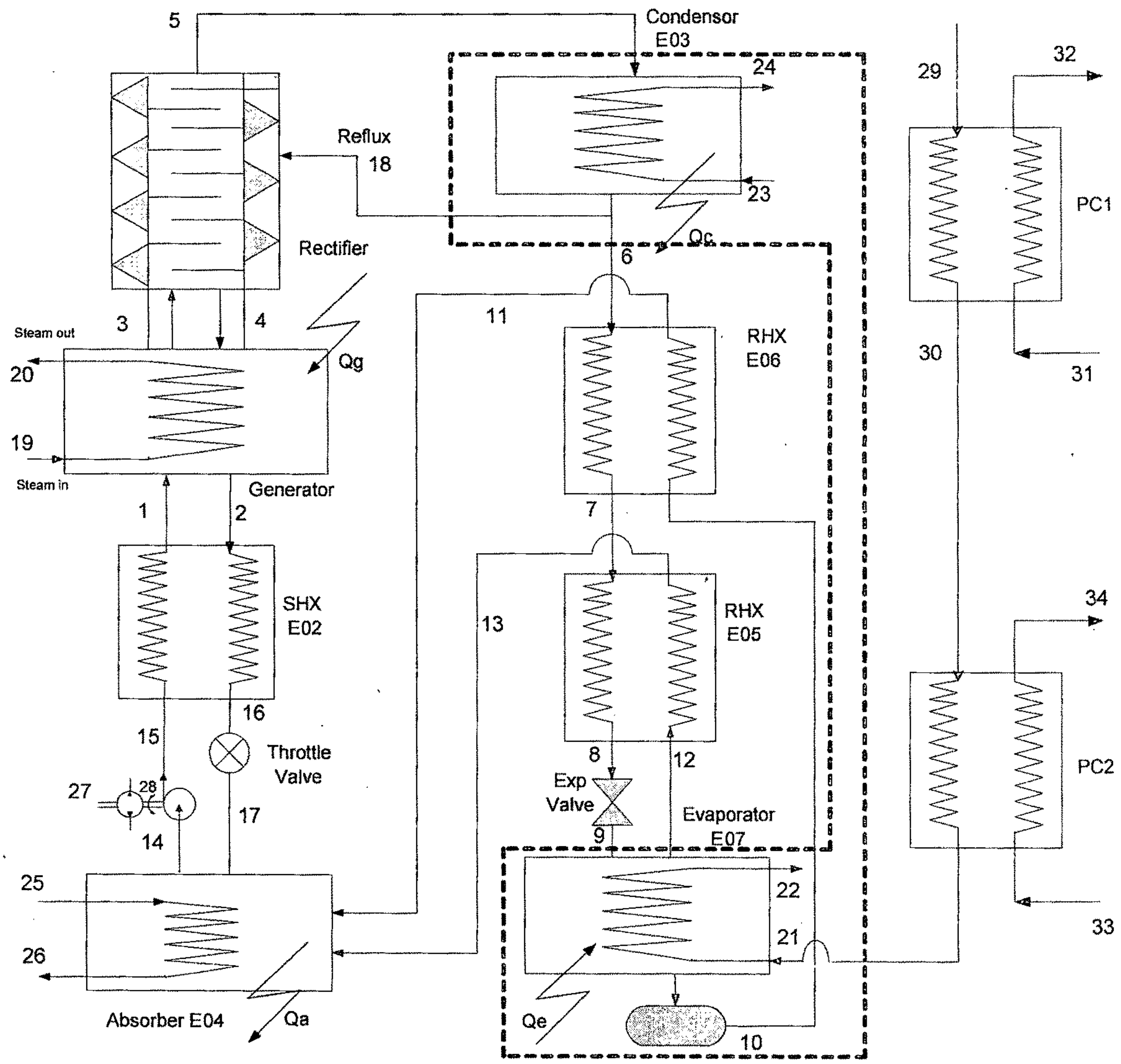

Fig. 5.1 Sub systems of AAVAR System for Exergoeconomic Optimization

5.1.2.3 Result and Discussion

Table 5.5 gives rate of exergy destruction, $\dot{E}_D$ and exergetic efficiency, ε for all the components of AAVAR system and Pre-cooler-1 and Pre-cooler-2 constituting the industrial brine chilling unit. It should be noted that Pre-cooler-1 and Pre-cooler-2 are excluded from components of AAVAR system and treated separately in exergy and exergoeconomic analysis.

Table 5.5 Exergetic Destruction, Loss and Efficiency Using EDM

Component	$\dot{E}_F$ kW	$\dot{E}_P$ kW	$\dot{E}_L$ kW	$\dot{E}_D$ kW	Y_D %	Y_L %	Y_D^* %	ε %
Generator	1640.00	1563.00	0	76.92	2.93	0	4.22	95.36
Rectifier	11536	11471	0	65.86	2.50	0	3.61	99.44
Cond.Evap.assly	784.30	226.90	114.50	443.71	16.96	4.38	24.35	28.93
SHX	1073.00	747.20	0	325.80	12.47	0	17.88	69.64
RHX 05	114.20	1.38	0	111.79	4.26	0	6.14	1.21
RHX 06	8.95	2.19	0	6.76	0.26	0	0.37	24.47
Solution pump	38.59	35.16	0	3.43	0.13	0	0.19	91.11
Absorber	101680	101437	163.60	78.68	3.01	6.26	4.32	99.76
Throttle Valve	---	---	---	26.63	1.00	---	1.46	---
Expansion Valve	---	---	---	30.76	1.18	---	1.68	---
Pre cooler-1	325.90	55.27	0	270.89	10.36	0	14.86	16.96
Pre cooler-2	608.70	228.20	0	380.80	14.57	0	20.90	37.49
Overall system	2613.19	510.37	278.10	1822.03	69.62	10.64	100	19.54

It is seen that 19.54 % of the exergy entering the system is converted to cooling effect which is the product of the system. The remaining exergy is either lost to the environment or destructed due to irreversibilities in the various components of the system. The rate of exergy destruction of the components of the system as compared with total fuel exergy input and net product (cooling produced) is given in Fig. 5.2 using Table 5.5. The total exergy supplied to the system is 2613.19 kW. Out of total exergy supplied as fuel, 19.54 % exergy is converted to useful product which is equivalent to 510.37 kW, 69.69 % exergy is destroyed which is equivalent to 1822.03 kW and remaining 10.64 % exergy is lost to environment which is equivalent to 278.1 kW.

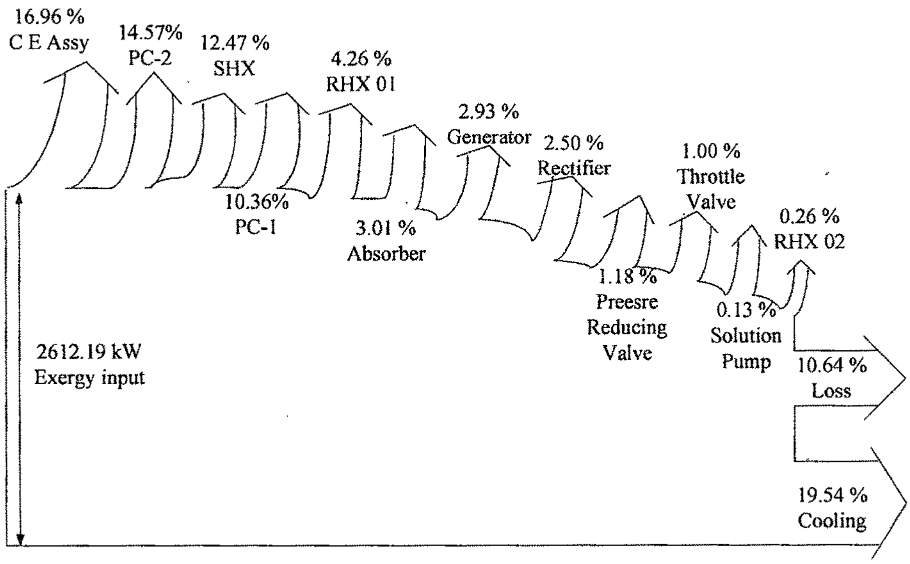

Fig. 5.2 Rate of Exergy Destruction of Various Components

The highest exergy destruction is found in condenser evaporator assembly. The total exergy destruction in this component is found to be 16.96 % of the total exergy supplied or 24.36 % of the total exergy destruction of the system. The reason for the highest exergy destruction may be attributed to the large temperature difference between the working fluid and brine in the evaporator and the working fluid and cooling water in the condenser.

The second highest exergy destruction is found to be in the pre-cooler-2 which amounts to be 380.5 kW and is equivalent to 20.93 % of the total exergy destruction and 14.57 % of the total exergy input. The effectiveness of pre-cooler-2 may be further increased by increasing the heat transfer area.

The third least efficient component in the system is solution heat exchanger having 69.64 % exergetic efficiency. This is due to the heat transfer across a high average temperature difference between the two unmixed streams in the heat exchanger. The improvement in the effectiveness of the solution heat exchanger may be possible by increasing heat transfer area.

The next highest exergy destruction is observed in the RHX 05 having the least exergetic efficiency of 1.21 % only. This heat exchanger is used to subcool the condensed refrigerant before entering in the evaporator. The high temperature difference between both the fluids and relatively very less mass flow rate of gaseous ammonia from the evaporator compared to the condensed ammonia from the condenser may be the reason for the poor exergetic efficiency. An increase in the convective heat transfer coefficient on gas side will improve the performance.

For RHX 06, the exergy destruction is less but the exergetic efficiency is quite low. The similar remedies can be used to improve the performance of this heat exchanger. The exergetic efficiencies of generator, rectifier, absorber and solution pump are 95.36 %, 99.44 %, 99.76 % and 91.11 %, respectively. It shows that the performance of these components is at the desired level. The expansion process in the expansion valve (V208) and pressure reducing process in throttle valve (V111) is irreversible and therefore, the exergy destruction in throttling valve and expansion valve is not avoidable.

The detailed exergy analysis of the large capacity industrial aqua ammonia vapour absorption refrigeration system presented here is well suited for finding the location, cause and true magnitude of the losses to be determined. This analysis enables for more effective utilization of energy resource and thereby having higher exergetic efficiency of the brine chilling unit using AAVAR system. The exergy analysis can now be extended for exergoeconomic analysis and exergoeconomic optimization which is a powerful tool to identify the entire cost source and designing the cost optimized AAVAR system

5.1.3 Entropy Generation Minimization (EGM) Method of Exergy Analysis

In this method of exergy analysis, the AAVAR system is divided in individual components (sub systems) considering them as an individual system. The entropy generation and the irreversibility defined based on Guoy-Stodola theorem at each of the sub system boundaries are calculated for all the components. Hence, the total irreversibility associated with the AAVAR system is estimated. The following are the component wise expressions for the entropy generation and irreversibility:

Generator

$$\dot{S}_g = \dot{m}_2 s_2 + \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_4 s_4 - \frac{Q_g}{T_{steam}} \tag{5.2}$$

$$I_g = T_0 \dot{S}_g \tag{5.3}$$

Rectifier

$$\dot{S}_r = \dot{m}_4 s_4 + \dot{m}_5 s_5 - \dot{m}_3 s_3 - \dot{m}_{18} s_{18} \tag{5.4}$$

$$I_r = T_0 \dot{S}_r \tag{5.5}$$

SHX

$$\dot{S}_{shx} = \dot{m}_1 s_1 + \dot{m}_{16} s_{16} - \dot{m}_2 s_2 - \dot{m}_{15} s_{15} \tag{5.6}$$

$$I_{shx} = T_0 \dot{S}_{shx} \tag{5.7}$$

Solution Pump

$$\dot{S}_{sp} = \dot{m}_{15} s_{15} - \dot{m}_{14} s_{14} \tag{5.8}$$

$$I_{sp} = T_0 \dot{S}_{sp} \tag{5.9}$$

Throttle Valve

$$\dot{S}_{tv} = \dot{m}_{17} s_{17} - \dot{m}_{16} s_{16} \tag{5.10}$$

$$I_{tv} = T_0 \dot{S}_{tv} \tag{5.11}$$

Absorber

$$\dot{S}_a = \dot{m}_{14} s_{14} - \dot{m}_{17} s_{17} - \dot{m}_{11} s_{11} - \dot{m}_{13} s_{13} + \frac{Q_a}{T_{atm}} \tag{5.12}$$

$$I_a = T_0 \dot{S}_a \tag{5.13}$$

Condenser

$$\dot{S}_c = \dot{m}_{18}\, s_{18} + \dot{m}_6\, s_6 - \dot{m}_5\, s_5 + \frac{Q_c}{T_{atm}} \tag{5.14}$$

$$I_c = T_0\, \dot{S}_c \tag{5.15}$$

RHX 06

$$\dot{S}_{rhx06} = \dot{m}_{11}\, s_{11} + \dot{m}_7\, s_7 - \dot{m}_6\, s_6 - \dot{m}_{10}\, s_{10} \tag{5.16}$$

$$I_{shx06} = T_0\, \dot{S}_{shx06} \tag{5.17}$$

RHX 05

$$\dot{S}_{rhx05} = \dot{m}_8\, s_8 + \dot{m}_{13}\, s_{13} - \dot{m}_7\, s_7 - \dot{m}_{12}\, s_{12} \tag{5.18}$$

$$I_{shx05} = T_0\, \dot{S}_{shx05} \tag{5.19}$$

Expansion Valve

$$\dot{S}_{ev} = \dot{m}_9\, s_9 - \dot{m}_8\, s_8 \tag{5.20}$$

$$I_{ev} = T_0\, \dot{S}_{ev} \tag{5.21}$$

Evaporator

$$\dot{S}_e = \dot{m}_{12}\, s_{12} + \dot{m}_{10}\, s_{10} - \dot{m}_9\, s_9 - \frac{Q_e}{T_{brine}} \tag{5.22}$$

$$I_e = T_0\, \dot{S}_e \tag{5.23}$$

Pre-cooler-1

$$\dot{S}_{pc1} = \dot{m}_{30}\, s_{30} + \dot{m}_{32}\, s_{32} - \dot{m}_{29}\, s_{29} - \dot{m}_{31}\, s_{31} \tag{5.24}$$

$$I_{pc1} = T_0\, \dot{S}_{pc1} \tag{5.25}$$

Pre-cooler-2

$$\dot{S}_{pc2} = \dot{m}_{21}\, s_{21} + \dot{m}_{34}\, s_{34} - \dot{m}_{30}\, s_{30} - \dot{m}_{33}\, s_{33} \tag{5.26}$$

$$\dot{I}_{pc2} = T_0\, \dot{S}_{pc2} \tag{5.27}$$

Total System

$$\begin{aligned} \dot{S}_{tot} = {} & \dot{S}_g + \dot{S}_r + \dot{S}_c + \dot{S}_{ev} + \dot{S}_{shx} + \dot{S}_{rhx05} + \dot{S}_{rhx06} + \dot{S}_{sp} + \dot{S}_{ab} + \\ & \dot{S}_{ev} + \dot{S}_{tv} + \dot{S}_{pc1} + \dot{S}_{pc2} \end{aligned} \tag{5.28}$$

$$\dot{I}_{tot} = T_0\, \dot{S}_{tot} \tag{5.29}$$

Eqs. 5.2 to 5.27 are used to estimate the entropy generation rate and irreversibility of processes in components. Eqs. 5.28 and 5.29 give, respectively total entropy generation rate and total irreversibility of the complete AAVAR system.

5.1.3.1 Results and Discussions

The outcome of the exergy analysis using EGM approach is given in Table 5.6. It is observed that the absorber is suffering from highest irreversibilities. This irreversibility may be due to irreversible mixing process of weak solution and ammonia vapour. The next highest irreversibility is observed in generator. It is recommended to increase the generator temperature. The components like condenser, evaporator, SHX, RHX05, RHX06, pre-cooler-1 and pre-cooler-2 are considered as simple heat exchanger and their irreversibilities can be reduced by improving their effectiveness. Using EGM method, the components like throttle valve and expansion valve can be analyzed, while EDM method cannot analyze components like expansion valve and throttle valve because fuel, product and loss cannot be defined for these components. The same problem is experienced for the components like condenser where product cannot be identified. Therefore, such components are analyzed by combining them with other components as an assembly where fuel, product and loss can be defined using EDM approach. For example, the combination of condenser and evaporator as a sub system helps in defining fuel, product and loss which in turn is used for exergoeconomic analysis. Considering the irreversibilities in throttle valve and pressure reducing valve equivalent to exergy destruction and combined with EDM.

Table 5.6 Results of EGM Approach of Exergy Analysis

Component	EGM $I = T_0 \Delta S_g$, kW	$I_R = \frac{I}{I_t}\%$
Generator	458.6	20.32
Rectifier	84.16	3.73
Condenser	265.50	5.60
Evaporator	200.50	8.88
SHX	325.80	14.43
RHX 05	19.19	0.85
RHX 06	11.14	0.49
Solution Pump	3.43	0.15
Absorber	533.10	23.62
Expansion Valve	30.76	1.36
Throttle Valve	26.04	1.15
Pre-cooler-1	149.10	6.61
Pre-cooler-2	288.80	12.80
Overall System	2257.12	100.00

From the above comparative study of two approaches of exergy analysis, viz. EGM and EDM, it can be concluded that the approach of EGM is quite convenient and useful to the extent of only up to exergy analysis. However, it is found difficult to combine it with economic analysis. Therefore, EDM method is followed in the present exergoeconomic analysis and optimization of AAVAR system.

5.2 Exergoeconomic Analysis

The essence of the economic analysis is the identification and inclusion of various cost heads incurred in the estimation of the total cost for the production. In the present case, the total cost involved in the cooling operation of brine consists of many cost heads. Thus, in general, the economic analysis of the system requires the estimation of levelized O & M cost of component ($\dot{Z}_k$) and fuel cost rate ($\dot{C}_f$). $\dot{Z}_k$ should be estimated for each component for brine chilling unit using TCI, β, γ and τ (Refer Eq.4.18). The fuel cost rate ($\dot{C}_f$) is governed by the source of heat energy used for the system. The estimation of $\dot{Z}_k$ and $\dot{C}_f$ are explained in the following section.

5.2.1 Levelized O & M cost ($\dot{Z}_k$)

To estimate $\dot{Z}_k$, TCI for each component should be estimated. The major components of the system such as generator, condenser, evaporator, absorber, SHX, RHX05 and RHX06 are considered as simple heat exchangers for the purpose of estimation of TCI. The costs of these heat exchangers are calculated based on weighted area method suggested by Peters et al. [158]. It should be noted that the data used by them are for the year 1990. Therefore, these costs are brought to the year 2009 with the help of M & S cost index as given in Section 4.2.2.3. The estimation of levelized O & M cost, ($\dot{Z}_k$) for various components are given below:

Generator

Generator used in the AAVAR is a 1-2 pass shell and tube heat exchanger with steam flowing through the tube made up of carbon steel and the strong aqua ammonia solution flowing through the shell with total heat transfer area of 517.4 m^2 (5570 ft^2). Fig. 5.3 gives purchased equipment cost for 1-2 shell and tube type heat exchanger and the equipment cost of the generator for the year 1990 is ₹ 1715000 ($35000). Using Table 4.1, the converted equipment cost for the year 2009 is estimated to be ₹ 19010000. Then, using Eq. 4.18, the levelized O&M cost for generator is found to be 278 ₹/hr as explained in Appendix C.

Rectifier

Rectifier is a packed tower made up of carbon steel similar to a cooling tower in construction. Fig. 5.4 gives the equipment cost of various tower constructions with respect to their diameter and height. The AAVAR system has the rectifier with diameter and height of 1.5 m (59 in) and 5 m (16.5 ft).

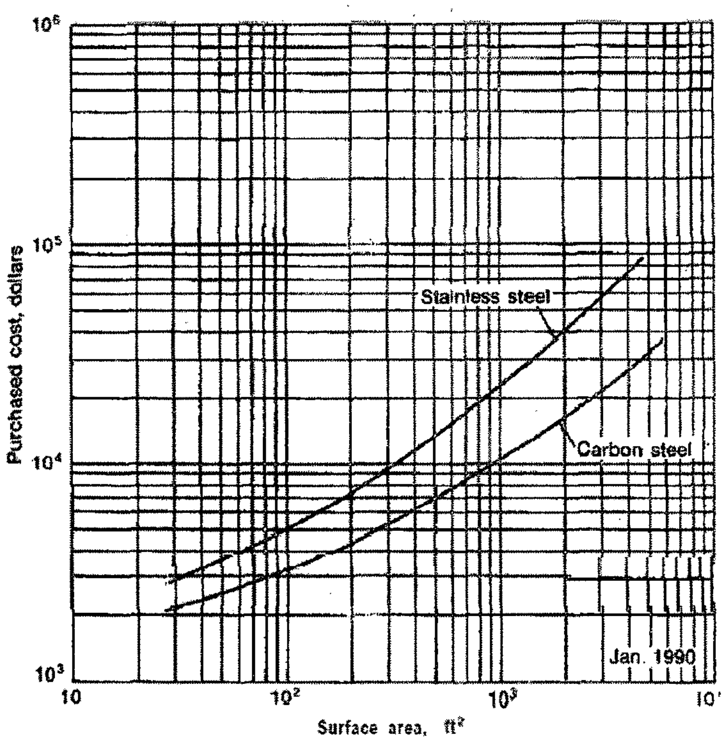

Fig. 5.3 Cost of U-Tube Type Shell & Tube Heat Exchanger [158]

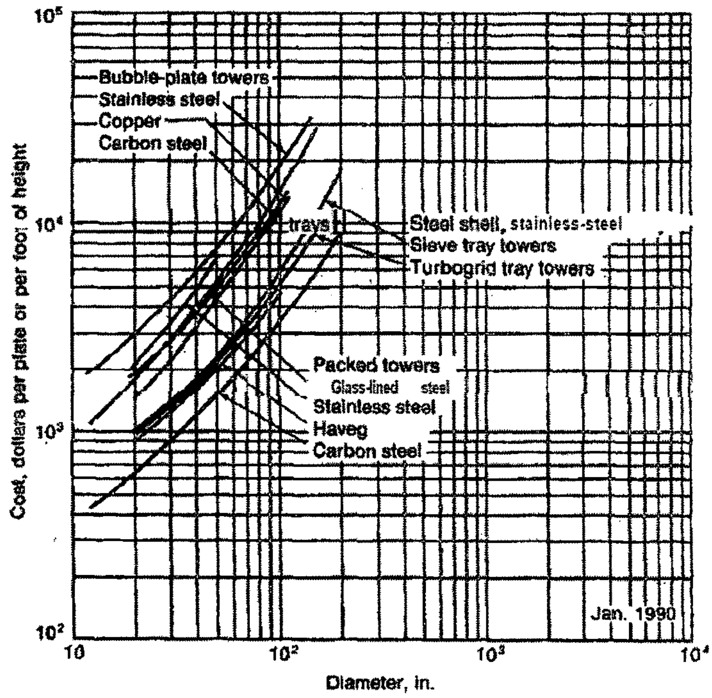

Fig. 5.4 Cost of Tower Including Installation [158]

Using Fig. 5.4, the purchase equipment cost for the year 1990 is found to be ₹ 1455300 ($29700). The equivalent cost for the year 2009 and the levelized O&M cost of rectifier are estimated, respectively at ₹ 2356000 and 235.9 ₹/hr.

Condenser

Condenser of AAVAR system is 1-2 pass shell and tube type heat exchanger of carbon steel material having cooling water flowing through tube side and ammonia vapour condensing on the shell side with total heat transfer area of 615.3 m^2 (6624 ft^2). Using Fig. 5.3, the cost for the year 1990 is found to be ₹ 1862000 ($38000). The equivalent cost for the year 2009 ₹ 2976636 the levelized O&M cost for condenser is found to be 301.9 ₹/hr.

Refrigerant Heat Exchanger (RHX 05)

RHX 05 is a shell and tube type heat exchanger with single shell and single tube pass having carbon steel tube with total heat transfer area of 273.1 m^2 (2940 ft^2) . Using Fig.5.5, the PEC for the year 1990 is ₹ 1127000 ($23000). The equivalent cost for the year 2009 will be ₹ 1801648. Therefore, the levelized O&M cost for RHX 05 is found to be 182.7 ₹/hr.

Refrigerant Heat Exchanger (RHX 06)

RHX 06 is a finned tube type heat exchanger with ammonia vapour condensing on the shell side and cooling water flowing through the tube. The tubes are 18 feet long and made up of carbon steel with 1.25 in. square pitch arrangement with total heat transfer area of 146.2 m^2 (1574 ft^2). Using Fig. 5.6, the PEC for the year 1990 is ₹ 1225000 ($25000) and the equivalent cost for the year 2009 is ₹ 1958313. Therefore, the levelized O&M cost for RHX 06 is found to be 198.5 ₹/hr.

Evaporator

Evaporator is a 1-2 pass shell and tube type heat exchanger with brine flowing through the tube and ammonia vaporizes in the shell with total heat transfer area of 1226 m^2 (13195 ft^2). Fig.5.3 gives the PEC with respect to the heat transfer area and carbon steel as tube material. The PEC for the year 1990 is ₹ 3822000 ($78000). The levelized O&M cost estimated for the evaporator is found to be 619.7 ₹/hr.

Absorber

Absorber is also a 1-2 pass shell and tube heat exchanger with cooling water flowing through the tube. Ammonia vapour from evaporator enters from side and weak

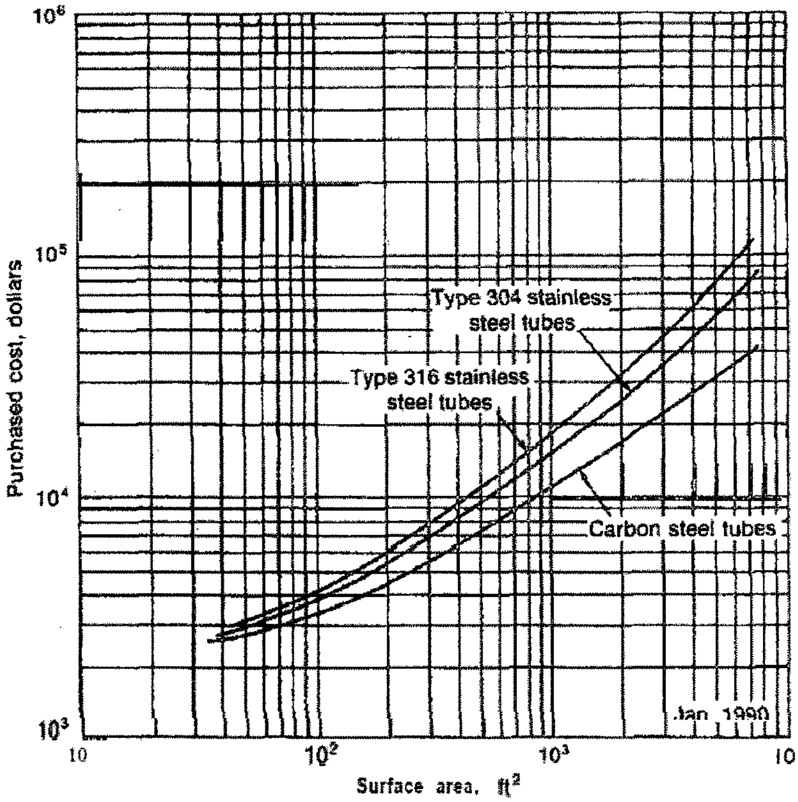

Fig. 5.5 Cost of Fixed Tube Sheet Type Heat Exchanger [158]

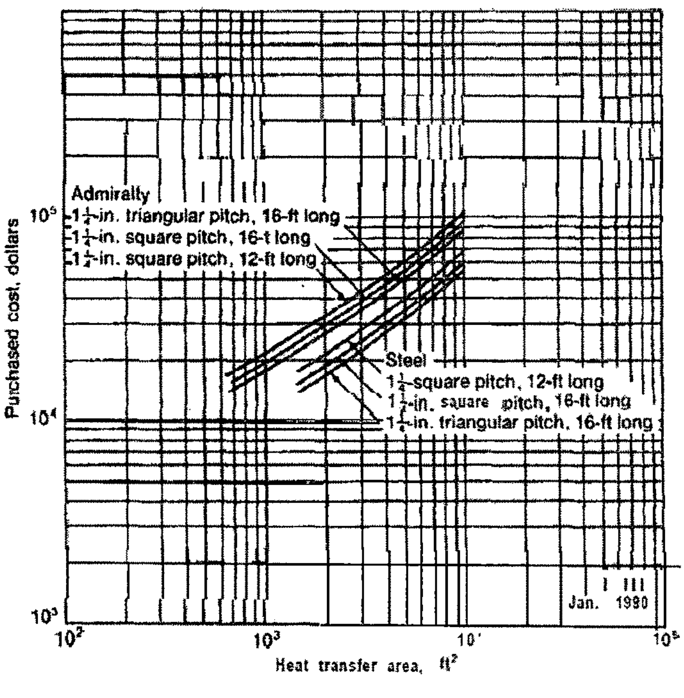

Fig. 5.6 Cost of Finned Tube Heat Exchanger with 1 in. Tube, 150 psi [158]

solution sprayed from the top in to the shell. The total heat transfer area in the absorber is 1772 m^2 (19072 ft^2). Using Fig.5.3, the PEC corresponding to the year 1990 is ₹ 5390000 ($110000) and the levelized O&M cost for absorber for carbon steel as tube material is found to be 874 ₹/hr.

Pump and Motor

Eqs. 5.30 and 5.31 give the relations for the estimation of equipment cost for pump and motor, respectively as suggested by Dentice d'Accadia [103]. The data provided along with the relation is for the year 1997. The M&S swift cost index for the year 1997 can be used for the estimation of the equipment cost for the year 2009.

$$Z_p = Z_{0p}\left(\frac{P_p}{P_{0p}}\right)^{m_p}\left(\frac{\eta_p}{1-\eta_p}\right)^{\eta_p} \tag{5.30}$$

Where Z_{0p} = $800, P_{0p} = 10 kW, m_p = 0.26, η_p = 0.5, P_p = 41.14 kW

$$Z_m = Z_{0m}\left(\frac{P_m}{P_{0m}}\right)^{m}\left(\frac{\eta_m}{1-\eta_m}\right) \tag{5.31}$$

Where Z_{0m} = $150, P_{0m} = 10 kW, m = 0.67, η_m = 0.8, P_m = 45.71 kW

The M&S swift cost index for the year 1997 is 1056.8. Using the above relations and data, the total levelized O&M cost for pump and motor $\dot{Z}_{pm}$ is found to be 19.38 ₹/hr.

Solution Heat Exchanger

SHX in AAVAR system is a double pipe heat exchanger having many hairpins made up of carbon steel with total heat transfer area of 1255 m^2 (13504 ft^2). Fig. 5.7 gives purchased equipment cost based on the heat transfer area for double pipe heat exchanger. Using the chart, the purchased equipment cost is ₹ 1125000 ($22959) in the year 1990. This cost is to be converted for the year 2009 for the purpose of the present analysis. The M&S cost index for the year 1990 was 915.1 while for the year 2009, it was 1462.9. Therefore, using Eq. 4.16, the purchased equipment cost for the year 2009 is estimated to be ₹ 1798000. Similarly, using Table 4.1, the other related costs of SHX are calculated and the TCI is estimated to be ₹ 12460000. Finally, using Eq. 4.18, the levelized O&M cost for SHX is found to be 182.2 ₹/hr.

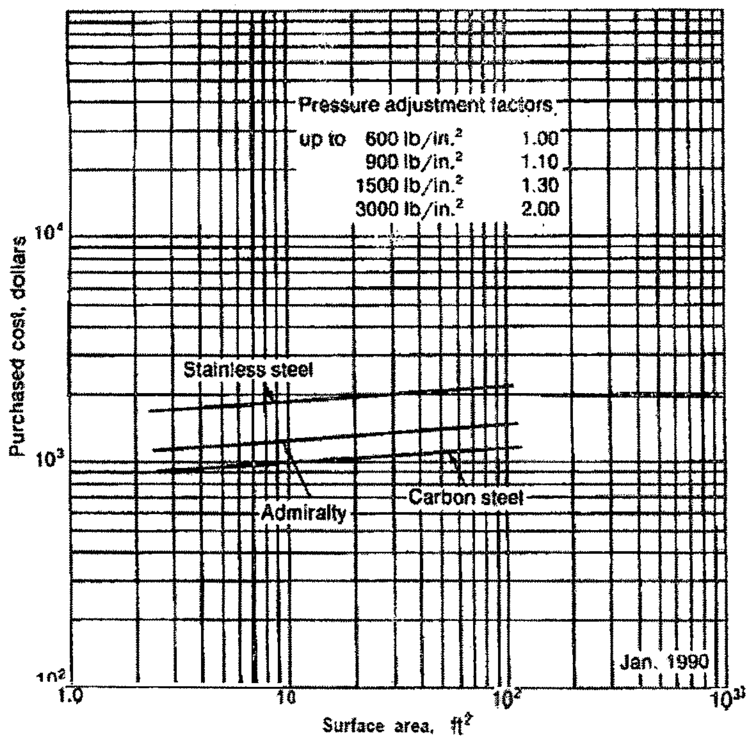

Fig. 5.7 Cost of Double Pipe Heat Exchanger [158]

Pre-cooler-1

Pre-cooler-1 is a fixed tube sheet type shell & tube heat exchanger having carbon steel as tube material. Brine flowing through the tube while ammonia vapour evaporates in the shell side with the total heat transfer area is at 81.43 m^2 (876.5 ft^2). Using Fig. 5.5, the PEC for the year 1990 is ₹ 49000 ($10000) and the levelized O&M cost is found to be 79.44 ₹/hr.

Pre-cooler-2

Pre-cooler-2 is also a similar type of shell & tube heat exchanger with carbon steel as tube material. Brine flowing through the tube while ammonia vapour evaporates in the shell with the total heat transfer area is 248.80 m^2 (2678 ft^2). Using Fig. 5.5, the PEC for the year 1990 is ₹ 1029000 ($21000) and the levelized O&M cost is found to be 166.7 ₹/hr.

The estimated values of $\dot{Z}_k$ for all the components of AAVAR including the pre-coolers 1 and 2 are given in Table 5.7. It can be seen that for each component of the

AAVAR system along with pre-coolers 1 and 2, a number of cost heads are involved in the estimation of TCI. TCI consists of FCI and Other Outlays. DC and IC constitute FCI, while Other Outlays consists of start up cost, working capital cost and allowance for funds. DC consists of on-site (ONSC) and off-site (OFSC) costs while IC consists of engineering & supervision, construction and contingency costs.

Table 5.7 Estimation of Levelized O & M Cost

Component	PEC ₹ (1)	Installation Cost 45 % of PEC (2)	Piping Cost 66 % of PEC (3)	Instru. & Control cost 20 % of PEC (4)	Electrical Equipment 11 % of PEC (5)	On Site Cost (ONSC) 1+2+3+4+5	Land 10 % of PEC (6)	Civil Work 60 % of PEC (7)	Service 65 % of PEC (8)	Of Site Cost (OFSC) (6+7+8)	Direct Cost (DC) ONSC + ONFC
Generator	2741639	1233738	1809482	548328	301580	6634767	274164	1644983	1782065	3701212	10335979
Rectifier	2326476	1046914	1535474	465295	255912	5630071	232648	1395886	1512209	3140743	8770814
Condenser	2976636	1339486	1964580	595327	327430	7203459	297664	1785982	1934813	4018459	11221918
Evaporator	6109937	2749472	4032558	1221987	672093	14786047	610994	3665962	3971459	8248415	23034462
SHX	1797732	808979	1186503	359546	197751	4350511	179773	1078639	1168526	2426938	6777449
RHX05	1801648	810742	1189088	360330	198181	4359989	180165	1080989	1171071	2432225	6792214
RHX06	1958313	881241	1292487	391663	215414	4739118	195831	1174988	1272903	2643722	7382840
Sol. Pump	191044	85970	126089	38209	21015	462327	19104	114626	124179	257909	720236
Absorber	8616579	3877461	5686942	1723316	947824	20852122	861658	5169947	5600776	11632381	32484503
Pre-cooler-1	783325	352496	516995	156665	86166	1895647	78333	469995	509161	1057489	2953136
Pre-cooler-2	1644983	740242	1085689	328997	180948	3980859	164498	986990	1069239	2220727	6201586

Continue

Table 5.7 Continue

Engg. & Supervision 30% of PEC (9)	Construction Cost 15 % of DC (10)	Contingency 20 % of FCI (11)	Indirect Cost (IC) (9+10+11)	Fixed Capital Investment (DC+IC)	Startup Cost 10% of FCI (12)	Working Capital 15 % of TCI (13)	Allowance For Funds 10% of PEC (14)	Other Outlays (12+13+14)	TCI (FCI+Other Outlays)	Levelized O&M Cost ₹/hr ($\dot{Z}_k$)
822492	1550397	1733027	4105916	14441895	1444189	2851809	274164	4570162	19012057	278
697943	1315622	1470597	3484162	12254976	1225498	2419963	232648	3878109	16133085	235.9
892991	1683288	1881572	4457851	15679769	1567977	3096249	297664	4961890	20641659	301.9
1832981	3455169	3862174	9150324	32184786	3218479	6355458	610994	10184931	42369717	619.7
539320	1016617	1136371	2692308	9469757	946976	1869972	179773	2996721	12466478	182.2
540494	1018832	1138846	2698172	9490386	949039	1874045	180165	3003249	12493635	182.7
587494	1107426	1237876	2932796	10315636	1031564	2037006	195831	3264401	13580037	198.5
57313	108035	120761	286109	1006345	100634	198721	19104	318459	1324804	19.38
2584974	4872675	5446657	12904306	45388809	4538881	8962826	861658	14363365	59752174	874
234998	442970	495150	1173118	4126254	412625	814802	78333	1305760	5432014	79.44
493495	930238	1039816	2463549	8665135	866513	1711085	164498	2742096	11407231	166.7

5.2.2 Fuel Cost

As mentioned earlier, the exergoeconomic analysis considers the steam used as the source of heat energy in AAVAR system as fuel. The cost of the fuel (steam) is taken as 322 ₹/1000 kg for the year 1990 as suggested by Peters et al. [158]. The fuel cost so obtained is to be updated to the processing year 2009. It can be carried out with the help of the economic term escalation rate (r_n) using Eq. 4.19. Thus, the fuel cost i.e., the cost rate associated with fuel (Steam) for the year 2009 is found to be 974 ₹ /1000 kg steam. However, from the cost data available from the fertilizer plant at GNSFC, Bharuch, Gujarat, the actual cost of steam for the generation of saturated steam at 15 bar is 900 ₹/1000 kg steam so the cost of steam considered is 0.9 ₹/kg steam. Similarly, the actual cost of generation of electricity from the captive power plant at GNSFC is 4 ₹/kWh, while the cost of purchased electricity from Gujarat Electricity Board is 6 ₹/kWh. It should be noted that all the above data are based on processing year 2009.

5.2.3 Cost flow

In Chapter 4, the principles for formulation of cost balance equations are explained (Refer Section 4.2.1). Applying the formulation of cost balance equations and the definition of fuel, product and loss (Refer Table 5.4); the exergoeconomic cost balance equations for each component of AAVAR system are formulated in the following forms:

Generator

As stated earlier, the purpose of the generator is to separate the refrigerant (ammonia vapour) from absorbent (water vapour) (stream 3, which is the stream passing through station 3) and the separated weak aqua ammonia solution returns back to absorber (stream 2). This is achieved by supplying ($\dot{E}_{19} - \dot{E}_{20}$) exergy of steam. The cost rate associated with steam ($\dot{C}_s$) is considered to be ₹ 900/1000 kg steam. The stream 2 and 3 are the product while stream 1 and 4 are the fuel for the generator.

$$c_1 \dot{E}_1 + c_4 \dot{E}_4 - c_2 \dot{E}_2 - c_3 \dot{E}_3 + \dot{C}_s + \dot{Z}_g = 0 \tag{5.32}$$

$$\frac{\dot{c}_3 \dot{E}_3-(\dot{c}_1 \dot{E}_1+\dot{c}_4 \dot{E}_4)}{\dot{E}_3-(\dot{E}_1+\dot{E}_4)}=\frac{\dot{c}_2 \dot{E}_2-(\dot{c}_1 \dot{E}_1+\dot{c}_4 \dot{E}_4)}{\dot{E}_2-(\dot{E}_1+\dot{E}_4)} \tag{5.33}$$

Here $\dot{c}$ is the unit exergy cost rate in terms of ₹/kJ

Rectifier

The purpose of the rectifier is to separate the unwanted water vapour from the ammonia vapour leaving the generator and going to the condenser (stream 5) by cooling it. The cooling of ammonia vapour which contains traces of water vapour is carried out by reflux (stream 18). Reflux is a portion of the condensed liquid refrigerant from the condenser flowing through RHX 05 and RHX 06 to evaporator. It is used to condense the traces of water vapour thus increase the quality of ammonia vapour going to the condenser. This results in the increase of the exergy of ammonia vapour coming out from rectifier. Stream 4 and 5 are the product while streams 3 and 18 are the fuel for rectifier.

$$\dot{c}_3 \dot{E}_3+\dot{c}_{18} \dot{E}_{18}-\dot{c}_5 \dot{E}_5-\dot{c}_4 \dot{E}_4+\dot{Z}_r=0 \tag{5.34}$$

$$\frac{\dot{c}_5 \dot{E}_5-(\dot{c}_3 \dot{E}_3+\dot{c}_{18} \dot{E}_{18})}{\dot{E}_5-(\dot{E}_3+\dot{E}_{18})}=\frac{\dot{c}_4 \dot{E}_4-(\dot{c}_3 \dot{E}_3+\dot{c}_{18} \dot{E}_{18})}{\dot{E}_4-(\dot{E}_3+\dot{E}_{18})} \tag{5.35}$$

SHX

Exergoeconomic analysis point of view, SHX transfers the exergy of the weak aqua ammonia solution (stream 2) coming from the generator to the strong aqua ammonia solution going to the generator (stream 1). Stream 2 acts as a fuel in SHX and unit exergy cost for stream 2 remains same at inlet and outlet of SHX as there is no exergy addition in between.

$$\dot{c}_{15} \dot{E}_{15}-\dot{c}_1 \dot{E}_1+\dot{c}_2 \dot{E}_2-\dot{c}_{16} \dot{E}_{16}+\dot{Z}_{shx}=0 \tag{5.36}$$

$$\dot{c}_2=\dot{c}_{16} \tag{5.37}$$

RHX 06

The portion of the un-evaporated liquid ammonia from the evaporator is to be evaporated before being allowed to enter the absorber. In RHX 06, the evaporation is achieved by using the condensed refrigerant (liquid ammonia) flowing to the absorber. Therefore, the exergy of liquid ammonia (refrigerant) leaving the condenser (stream 6) is transferred to the un-evaporated ammonia (refrigerant) flowing from the evaporator to the absorber.

$$\dot{c}_6 \dot{E}_6 - \dot{c}_7 \dot{E}_7 + \dot{c}_{10} \dot{E}_{10} - \dot{c}_{11} \dot{E}_{11} + \dot{Z}_{rhx06} = 0 \tag{5.38}$$

$$\dot{c}_{10} = \dot{c}_{11} \tag{5.39}$$

RHX 05

In RHX 05, the exergy of liquid ammonia (refrigerant), leaving RHX 06 (stream 7) is transferred to the vapour ammonia (refrigerant) (stream 12) leaving the evaporator.

$$\dot{c}_7 \dot{E}_7 - \dot{c}_8 \dot{E}_8 + \dot{c}_{12} \dot{E}_{12} - \dot{c}_{13} \dot{E}_{13} + \dot{Z}_{rhx05} = 0 \tag{5.40}$$

$$\dot{c}_{12} = \dot{c}_{13} \tag{5.41}$$

Condenser

The high pressure ammonia vapour (refrigerant) from the rectifier (stream 5) is condensed in the condenser using cooling water circulated through the cooling tower as the cooling medium.

$$\dot{c}_5 \dot{E}_5 - \dot{c}_6 \dot{E}_6 - \dot{c}_{18} \dot{E}_{18} - \dot{C}_c + \dot{Z}_c = 0 \tag{5.42}$$

$$\dot{c}_5 = \dot{c}_6 \tag{5.43}$$

$$\dot{c}_{18} = \dot{c}_6 \tag{5.44}$$

Where, $\dot{C}_c$ is the cost rate associated with exergy loss from the condenser.

Absorber

The vapour ammonia from the evaporator flowing through RHX 05 and the evaporated vapour ammonia from RHX 06 are both absorbed by the weak aqua ammonia solution from the generator.

$$\dot{c}_{17} \dot{E}_{17} - \dot{c}_{14} \dot{E}_{14} + \dot{c}_{13} \dot{E}_{13} + \dot{c}_{11} \dot{E}_{11} - \dot{C}_a + \dot{Z}_a = 0 \tag{5.45}$$

Pressure Reducing Valve

Across the pressure reducing valve, no exergy transfer takes place so unit exergy cost remains same

$$\dot{c}_{16} = \dot{c}_{17} \tag{5.46}$$

$$\frac{\dot{c}_{14}\dot{E}_{14}}{\dot{E}_{14}}=\frac{\dot{c}_{17}\dot{E}_{17}+\dot{c}_{13}\dot{E}_{13}+\dot{c}_{11}\dot{E}_{11}}{\dot{E}_{17}+\dot{E}_{13}+\dot{E}_{11}} \tag{5.47}$$

Evaporator

$$\dot{c}_9\dot{E}_9-\dot{c}_{12}\dot{E}_{12}-\dot{c}_{10}\dot{E}_{10}-\dot{C}_p+\dot{Z}_e=0 \tag{5.48}$$

$$\frac{\dot{c}_{12}\dot{E}_{12}-\dot{c}_9\dot{E}_9}{\dot{E}_{12}-\dot{E}_9}=\frac{\dot{c}_{10}\dot{E}_{10}-\dot{c}_9\dot{E}_9}{\dot{E}_{10}-\dot{E}_9} \tag{5.49}$$

Pump and Motor

$$\dot{c}_{14}\dot{E}_{14}-\dot{c}_{15}\dot{E}_{15}+\dot{C}_m+\dot{Z}_{pm}=0 \tag{5.50}$$

$\dot{C}_m$ is the cost rate of electricity in ₹/sec

Condenser - Evaporator Combined

The evaporator and condenser (heat dissipative component) are combined in to single unit for the purpose of cost flow analysis as discussed earlier. The cost rate associated with the capital investment for the condenser-evaporator combined and cost rates associated with the exergy losses are accounted to the final product.

$$\dot{c}_5\dot{E}_5-\dot{c}_{18}\dot{E}_{18}-\dot{c}_6\dot{E}_6+\dot{c}_8\dot{E}_8-\dot{c}_{12}\dot{E}_{12}-\dot{c}_{10}\dot{E}_{10}-\dot{C}_p-\dot{C}_c+\dot{Z}_{EA}=0 \tag{5.51}$$

$$\dot{Z}_{EA}=\dot{Z}_c+\dot{Z}_e$$

AAVAR System

Using the cost rate associated with each components of AAVAR system excluding the pre-coolers-1 and 2, the total levelized O & M cost, Z_{tot} can be estimated. Then for the overall system, the following relation can be formulated

$$\dot{C}_s+\dot{C}_m-\dot{C}_c-\dot{C}_a-\dot{C}_p+\dot{Z}_{tot}=0$$

$$\dot{Z}_{tot}=\dot{Z}_g+\dot{Z}_r+\dot{Z}_{shx}+\dot{Z}_{06}+\dot{Z}_{05}+\dot{Z}_c+\dot{Z}_a+\dot{Z}_{pm}+\dot{Z}_e \tag{5.52}$$

Pre-cooler-1

$$\dot{c}_{29}\dot{E}_{29}-\dot{c}_{30}\dot{E}_{30}+\dot{c}_{31}\dot{E}_{31}-\dot{c}_{32}\dot{E}_{32}+\dot{Z}_{pc1}=0 \tag{5.53}$$

$$\dot{c}_{29}=\dot{c}_{30} \tag{5.54}$$

$$\dot{c}_{31} = \dot{c}_{32} \tag{5.55}$$

Pre-cooler-2

$$\dot{c}_{30}\,\dot{E}_{30} - \dot{c}_{21}\,\dot{E}_{21} + \dot{c}_{33}\,\dot{E}_{33} - \dot{c}_{34}\,\dot{E}_{34} + \dot{Z}_{pc2} = 0 \tag{5.56}$$

$$\dot{c}_{21} = \dot{c}_{30} \tag{5.57}$$

$$\dot{c}_{33} = \dot{c}_{34} \tag{5.58}$$

Out of these variables $\dot{c}_1 ... \dot{c}_{18}, \dot{c}_{29} ... \dot{c}_{34}, \dot{C}_p, \dot{C}_a, \dot{C}_c, \dot{C}_s$ and $\dot{C}_m$, the last two are the cost of fuel in generator and electricity for solution pump, respectively. Under the normal operation of the AAVAR system, both of them are known data. The remaining 27 are calculated by solving Eqs. 5.32 to 5.58 using EES software. The cost per unit exergy, c (₹/kJ) and cost flow rate, $\dot{C}$ (₹/sec) for each stream of the system are calculated and given in Table 5.8.

After calculating the cost of product at evaporator (cooling), the cost of exergy flows related to pre-cooler-1 and pre-cooler-2 ($\dot{c}_{29}$ to $\dot{c}_{34}$) are calculated separately using known values of $\dot{E}_1 ... \dot{E}_{19}$ and $\dot{E}_{29} ... \dot{E}_{34}$. The unit exergy flows associated with streams 1 to 34 are given in Table 5.8.

5.2.4 Exergoeconomic Evaluation

AAVAR system can now be exergoeconomically evaluated through exergoeconomic parameters, viz. fuel cost per unit exergy ($c_{F,k}$), product cost per unit exergy ($c_{p,k}$), exergetic destruction cost rate ($\dot{C}_{D,k}$), exergetic cost rate associated with loss ($\dot{C}_{L,k}$), relative cost difference (r_k),exergoeconomic factor (f_k) and exergetic efficiency (ε_k). Based on the methodology suggested by Bejan et al. [155] and discussed in Section 4.2.3 of Chapter 4, the above parameters are estimated using Eqs. 4.20 to 4.27 and given

Table 5.8 Unit Exergy Cost and Cost Flow Rate

Flows	Unit exergy cost c, ₹ /kJ	Exergy flow $\dot{E}$, kW	Cost flow rate $\dot{C}$, ₹/sec
1	0.002949	102220	301.4
2	0.002934	50806	149.1
3	0.002936	53329	156.6
4	0.003655	352.4	1.288
5	0.002936	64800	190.2
6	0.002936	52646	154.6
7	0.002937	52644	154.6
8	0.002945	52645	155
9	0.002948	52614	155.1
10	0.002918	4652	13.57
11	0.002918	4643	13.55
12	0.002948	47444	139.8
13	0.002948	47330	139.5
14	0.002939	101437	298.2
15	0.002940	101473	298.2
16	0.002934	49733	145.9
17	0.002934	49707	145.8
18	0.002936	11888	34.9
19-20	----	----	2.83
22-21	----	----	1.85
24-23	----	----	0.87
26-25	----	----	0.96
28-27	----	----	0.05
29	0.008172	0.06	0.0005
30	0.008172	55.33	0.45
31	0.001318	52218	68.81
32	0.001318	51892	68.38
33	0.002986	58155	173.60
34	0.002986	57546	171.8

in Table 5.9. The evaluation of exergoeconomic parameters for generator is explained in Appendix D.

It is obvious that higher values of r_k and $\dot{C}_{D,k}$ in a given component indicates a poor performance both energy utilization and economic points of view. Therefore, more attention should be paid to this component during optimization. Pre-cooler-1 and pre-cooler-2 are independent components and the variation in the controlling parameter of both the pre-coolers does not affect directly the performance of AAVAR system. Therefore, the optimization of both the pre-coolers can be carried out independently.

Table 5.9 Parameters of Exergoeconomic Evaluation

Component	$c_{F,k}$ ₹/MJ	$c_{p,k}$ ₹/MJ	$\dot{C}_{D,k}$ ₹/hr	$\dot{C}_{L,k}$ ₹/hr	$\dot{Z}_k$ ₹/hr	f_k %	r_k %	ε %
Generator	1.72	1.86	474.30	0	278	36.96	7.82	95.36
Rectifier	2.92	2.94	683.90	0	235.90	25.65	0.75	99.44
Cond Evap Assembly	3.12	8.15	4979	1287	921.60	12.82	161.20	28.93
SHX	2.93	4.17	3441	0	182.20	5.028	42.18	69.64
RHX 05	2.95	424.10	1182	0	182.70	13.38	14286	1.21
RHX 06	2.92	23.39	71.01	0	198.50	73.65	701.40	24.47
Sol Pump	1.18	5.76	14.57	0	19.38	57.09	388	91.11
Absorber	2.94	2.94	832.70	1731	874	25.42	0.03	99.76
Pre-cooler-1	1.32	8.17	1284	0	79.44	5.83	520	16.96
Pre-cooler-2	2.97	8.17	4090	0	166.70	3.92	173.70	37.49
VAR System	1.71	8.15	7182	1710	2892	24.54	377.4	13.52
Overall System	1.96	8.16	12820	1960	3138	17.51	316.90	19.54

5.2.4.1 Results and Discussions

A comparison of the r value, one of the parameters of exergoeconomic evaluation of AAVAR system, given in Table 5.9, shows that the r value for RHX 05 is highest among the entire components. Therefore, attention should be paid to this component. RHX 05 has the lowest exergetic efficiency among all components and possesses one of the higher level exergy destruction. Therefore, improvement of exergetic efficiency of RHX 05 should be considered at the cost of capital investment.

RHX 06 is having second highest r value with low exergetic efficiency and low exergy destruction. It shows that there is a scope for improvement in the exergetic efficiency of the VAR system by increasing the effectiveness of RHX 06. Solution pump is the next candidate, having high value of r and f which shows that the investment cost of the pump can be reduced at the cost of exergetic efficiency.

The next component is condenser-evaporator assembly having higher value of r and lower value of f due to high exergy destruction and low exergetic efficiency. Therefore the exergetic efficiency of condenser evaporator assembly should be improved at the cost of capital investment by increasing the heat exchanger area. Exergy destruction at evaporator can be reduced by increasing the ammonia temperature at evaporator inlet and the evaporator pressure. The next component in that order is solution heat exchanger (SHX). It is having low value of f due to very high value of exergy destruction. It is suggested that the exergetic efficiency of the SHX should be improved through increase in its effectiveness.

The component having next highest r value is generator. It is having high f value so higher investment cost. Further, generator possesses slight potential for reducing exergy destruction cost by increasing its temperature. The next one is the rectifier, where there is no one direct decision variable controlling the performance but depends on generator and condenser temperatures. Therefore, the effect of generator and condenser temperature on the rectifier performance is observed during global optimization. The next component in the order is absorber which has very less value and high exergetic efficiency. So this component is working properly.

Both the pre-coolers are having very high r value and hence high exergy destruction cost. By increasing the heat transfer area, the exergy destruction should be reduced and exergetic efficiency should be improved. It is interesting to note that pre-cooler-1 has half the exergetic efficiency as compared to that of pre-cooler-2. The reason for such a large difference in exergetic efficiency is the difference in exergy of product in both pre-coolers. In pre-cooler-1, the cooling of brine is carried out up to 15.9°C with exergy flow equal to 55.33 kW. While in pre-cooler-2, the brine is cooled up to 5.40°C with exergy flow 283.50 kW as given in Table 5.3. So pre-cooler-2 works with very high exergy level, therefore having high exergetic efficiency.

5.3 Exergoeconomic Optimization

The exergoeconomic optimization of the system requires a thermodynamic model and a cost model. The thermodynamic model gives the performance prediction of the system with respect to some thermodynamic variables such as exergy destruction, exergy loss and exergetic efficiency. The cost model permits detailed calculation of cost values for a given set of the thermodynamic variables. For each component, it is expected that the investment cost increases with increasing capacity and increasing exergetic efficiency.

5.3.1 Estimation of B_k, n_k and m_k

After evaluation of parameters of exergoeconomic evaluation for each component, the exergoeconomic optimization of the system is carried out at component level using the method suggested in Chapter 4, Section 4.3. To solve Eq. 4.29 for local optimum, the parameters B_k, n_k and m_k are to be evaluated through curve fitting technique as explained for the following cases

Generator

In order to determine the local optimum for exergoeconomic optimization of generator as an individual component of AAVAR, the parameters B_k, n_k and m_k are to be evaluated through curve fitting technique. For this purpose, generator temperature t_G is considered as decision variable. The generator temperature t_G is varied from 142°C to 152°C, and necessary parameters are estimated using the method discussed in Chapter4, Section 4.3 and is given in Table 5.10.

It can be seen from the power law ($y = Bx^n$) in Fig. 5.8 that the values of B_G and n_G are 226231 and 0.048, respectively {Section 4.3 using Eq.4.29}

Table 5.10 Generated Data Using Investment Cost Equation for Generator

T_G °C	$\dot{E}_{PG}$ kW	$\dot{E}_{D,G}$ kW	$TCI_G / \dot{E}_{P,G}^{0.66}$	$\dot{E}_{P,G} / \dot{E}_{D,G}$
142	1634	28818	197134	0.05670
143	1642	28834	197196	0.05694
144	1650	28851	197250	0.05718
145	1658	28867	197300	0.05742
146	1666	28884	197346	0.05766
147	1674	28901	197389	0.05791
148	1682	28917	197429	0.05816
149	1690	28934	197460	0.05841
150	1698	28950	197492	0.05866
151	1707	28967	197517	0.05892
152	1715	28983	197539	0.05917

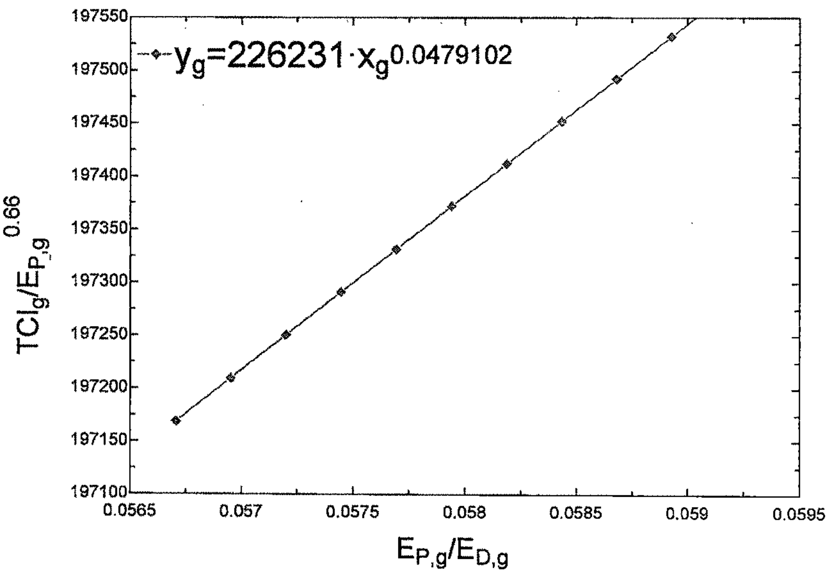

Fig. 5.8 Plot of TCI v/s Exergetic Efficiency for Generator

Condenser- Evaporator (C-E) Assembly

For condenser-evaporator assembly, evaporator temperature is the decision variable. With change in evaporator temperature, the temperature at which, chilling effect produced will change. This will change mean temperature at evaporator and heat loss at condenser which will increase the cost of condenser-evaporator assembly. Considering evaporator temperature as decision variable at different evaporator temperature, and using investment cost equation, Table 5.11 is obtained. In the optimization process for the condenser-evaporator assembly, condenser temperature and absorber temperature also can be considered as decision variables and can be the same. Therefore, analysis is carried out by considering condenser and absorber temperatures at three different temperature levels at 36°C, 38°C and 40°C. Tables 5.11 to 5.13 give the generated data for a range of evaporator temperature from - 20°C to -15°C with the condenser and absorber temperatures at 36°C, 38°C and 40°C, respectively.

Table 5.11 Generated Data Using Investment Cost Equation for CE Assembly (Ta = Tc = 36°C)

T_{evap} °C	$\dot{E}_{p,ce}$ kW	$\dot{E}_{D,ce}$ kW	$I_{ce} / \dot{E}_{p,ce}^{0.66}$	$\dot{E}_{P,ce} / \dot{E}_{D,ce}$
-20	226.9	1156	1.53E+06	0.1963
-19	226.9	1130	1.53E+06	0.2008
-18	226.9	1105	1.53E+06	0.2054
-17	226.9	1079	1.53E+06	0.2102
-16	226.9	1054	1.53E+06	0.2152
-15	226.9	1030	1.53E+06	0.2204

Table 5.12 Generated Data Using Investment Cost Equation for CE assembly (Ta = Tc = 38°C)

T_{evap} °C	$\dot{E}_{p,ce}$ kW	$\dot{E}_{D,ce}$ kW	$I_{ce} / \dot{E}_{p,ce}^{0.66}$	$\dot{E}_{P,ce} / \dot{E}_{D,ce}$
-20	226.9	1134	1.53E+06	0.2002
-19	226.9	1108	1.53E+06	0.2048
-18	226.9	1083	1.53E+06	0.2096
-17	226.9	1057	1.53E+06	0.2146
-16	226.9	1032	1.53E+06	0.2198
-15	226.9	1008	1.53E+06	0.2252

Table 5.13 Generated Data Using Investment Cost Equation for CE assembly (Ta = Tc = 40°C)

T_{evap}	$\dot{E}_{p,ce}$	$\dot{E}_{D,ce}$	$I_{ce} / \dot{E}_{p,ce}^{0.66}$	$\dot{E}_{P,ce}/ \dot{E}_{D,ce}$
-20	226.9	1112	1.53E+06	0.2041
-19	226.9	1086	1.53E+06	0.2089
-18	226.9	1061	1.53E+06	0.2139
-17	226.9	1036	1.53E+06	0.2191
-16	226.9	1011	1.53E+06	0.2245
-15	226.9	985.9	1.53E+06	0.2301

In order to determine the local optimum for exergoeconomic optimization of condenser-evaporator together as an individual component of AAVAR, the parameters B_k, n_k and m_k are to be evaluated through curve fitting technique which is carried out using Figs. 5.9 to 5.11. Fig. 5.9 gives the value of $B_{ce} = 1.54\times10^6$ and $n_{ce} = 0.059$ when T_a = T_c = 36°C. The value of $B_{ce} = 1.54\times10^6$ and $n_{ce} = 0.058$ are obtained through regression fit using Fig. 5.10 when T_a = T_c = 38°C. Fig. 5.11 gives the value of $B_{ce} = 1.54\times10^6$ and $n_{ce} = 0.057$ when the condenser and absorber temperatures are same at 40°C.

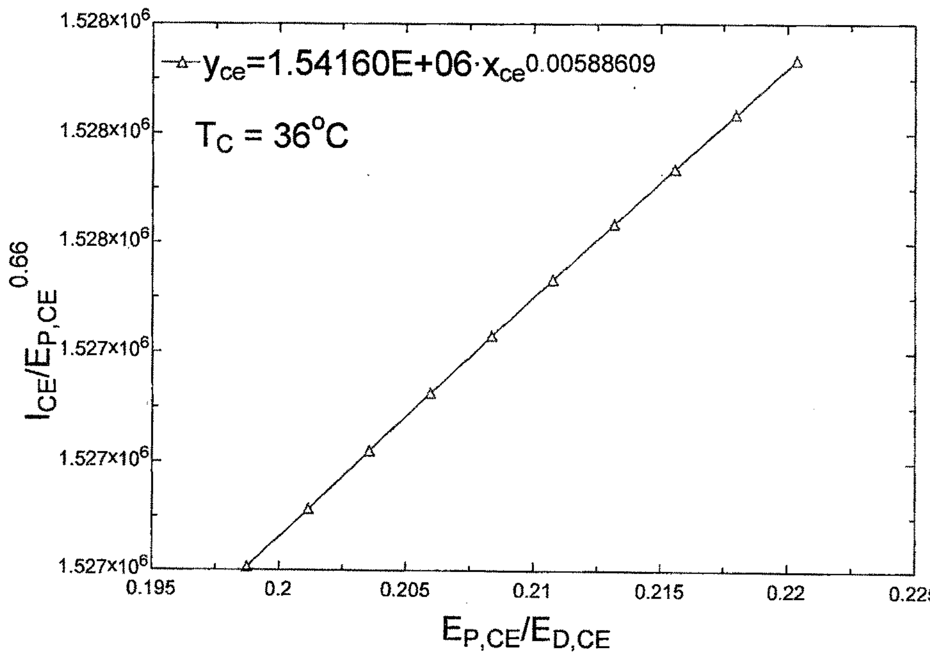

Fig. 5.9 Plot of TCI v/s Exergetic Efficiency for C-E Assembly for Ta = Tc = 36°C

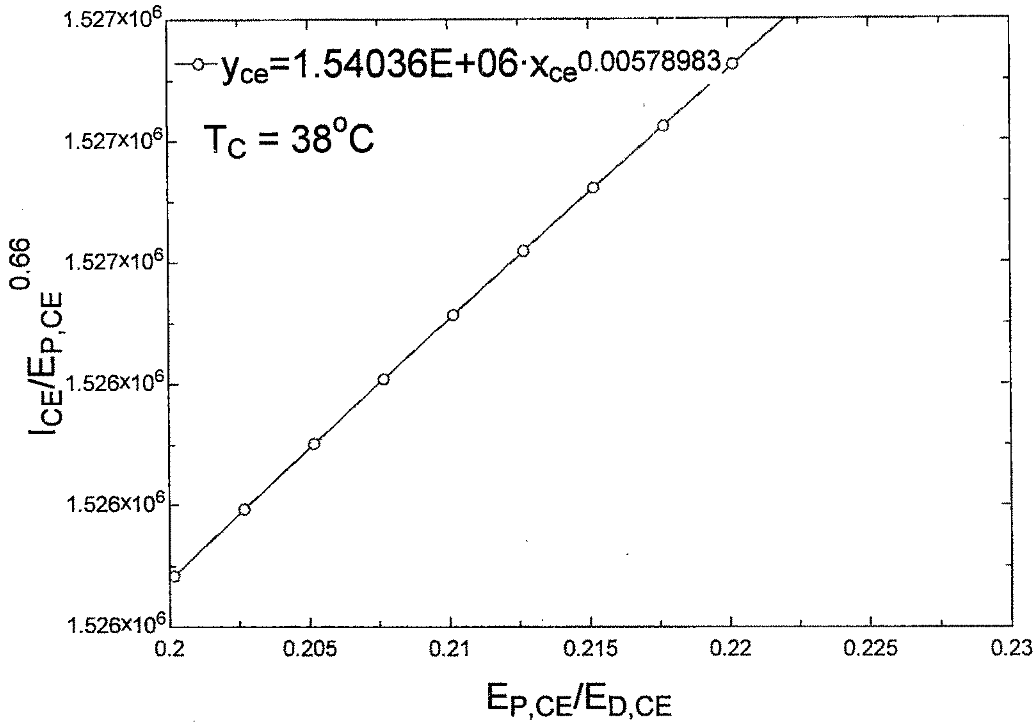

Fig. 5.10 Plot of TCI v/s Exergetic Efficiency for C-E Assembly for Ta = Tc = 38°C

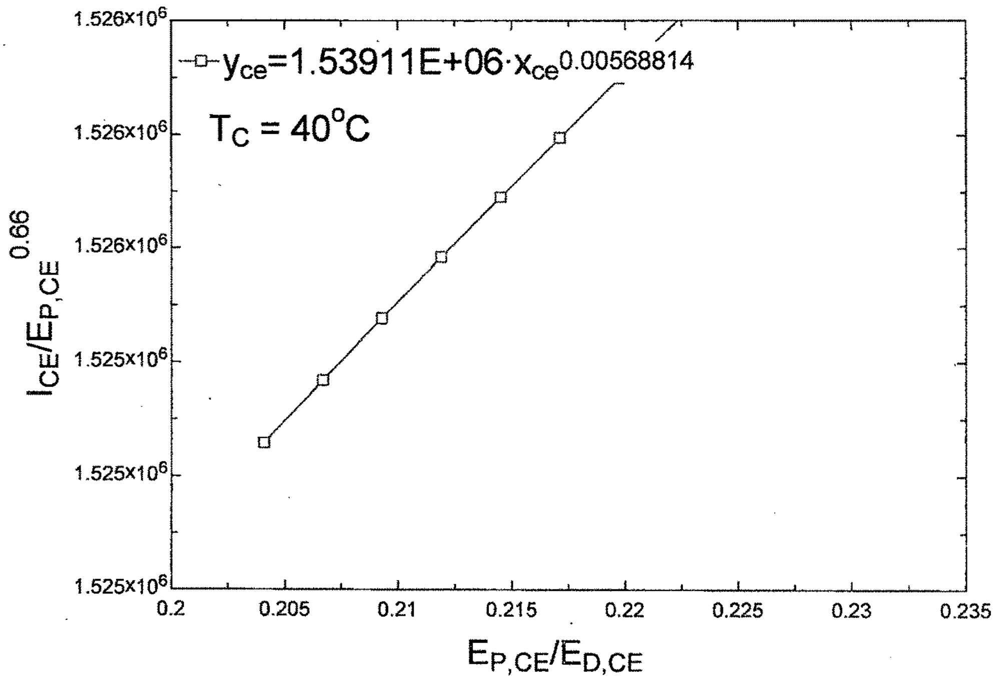

Fig. 5.11 Plot of TCI v/s Exergetic Efficiency for C-E Assembly for T_a = T_c = 40°C

Table 5.14 Generated Data Using Investment Cost Equation for SHX

χ_{shx}	$\dot{E}_{p,shx}$ kW	$\dot{E}_{D,shx}$ kW	$I_{shx} / \dot{E}_{p,shx}^{0.16}$	$\dot{E}_{P,shx} / \dot{E}_{D,shx}$
0.75	676.00	354.70	4510	1.91
0.77	704.30	342.10	4902	2.06
0.79	733.00	328.40	5349	2.23
0.81	762.20	313.60	5865	2.43
0.83	791.90	297.50	6468	2.66
0.85	822.00	280.20	7185	2.93
0.87	852.60	261.70	8052	3.26
0.89	883.50	242.10	9128	3.65
0.91	914.90	221.20	10508	4.14
0.93	946.80	199.10	12361	4.76

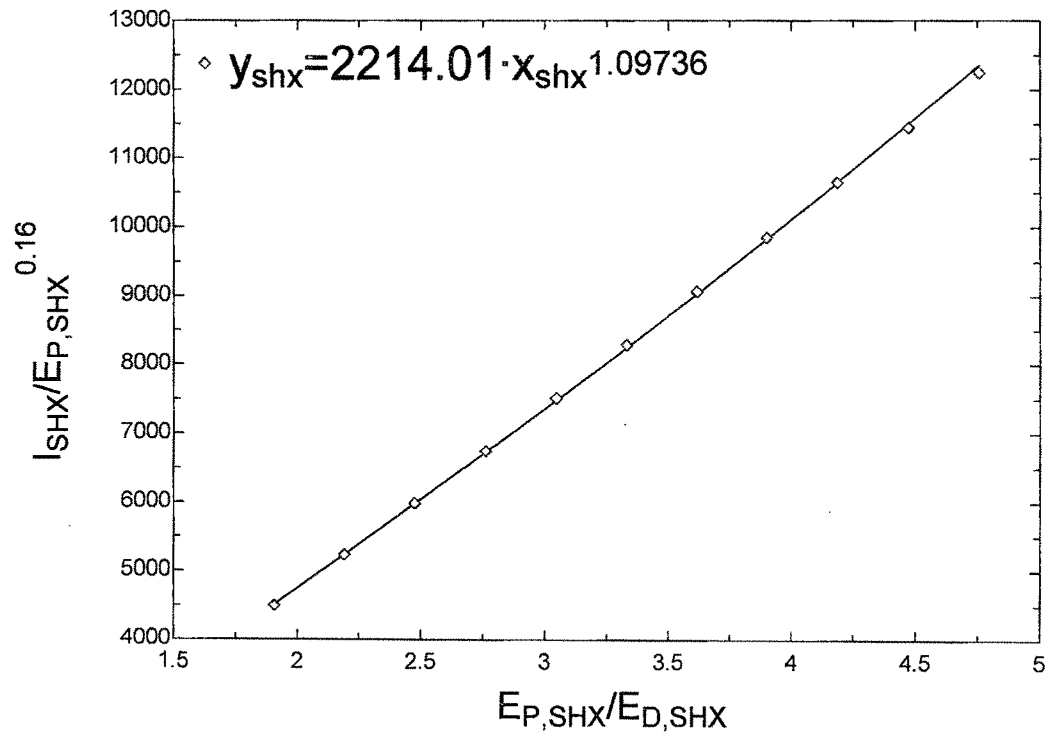

Fig. 5.12 Plot of TCI v/s Exergetic Efficiency for SHX

SHX

As the purpose of SHX is to recover the waste energy from weak solution and to heat strong solution going to generator, the effectiveness of heat exchanger is considered as decision variable. By improving the effectiveness, the recovered heat will increase and exergy destruction will decrease. The values of m_{shx} is equal to 0.16 equivalent to scaling exponent α as SHX is a double pipe heat exchanger [155]. Table 5.14 gives the generated data for regression to obtain B_{shx} and n_{shx}. From Fig. 5.12, the values of B_{shx} and n_{shx} are found to be 2214 and 1.097, respectively.

RHX 05

As stated earlier, RHX 05 is a shell and tube type heat exchanger with single shell and single tube pass. The effectiveness of heat exchanger is considered as decision variable. The value of m_{RHX05} is to be taken as 0.66. Table 5.15 gives the generated data and Fig.5.13 gives the values of B_{RHX05} = 602445 and n_{RHX05} = 0.267

Table 5.15 Generated Data Using Investment Cost Equation for RHX 05

χ_{RHX05}	$\dot{E}_{p,RHX05}$ kW	$\dot{E}_{D,RHX05}$ kW	$I_{RHX05} / \dot{E}_{p,RHX05}^{0.66}$	$\dot{E}_{P,RHX05} / \dot{E}_{D,RHX05}$
0.490	0.9730	112.3	172449	0.008667
0.487	0.8886	112.6	162841	0.007894
0.484	0.8052	112.9	158933	0.007134
0.481	0.7227	113.2	158546	0.006387

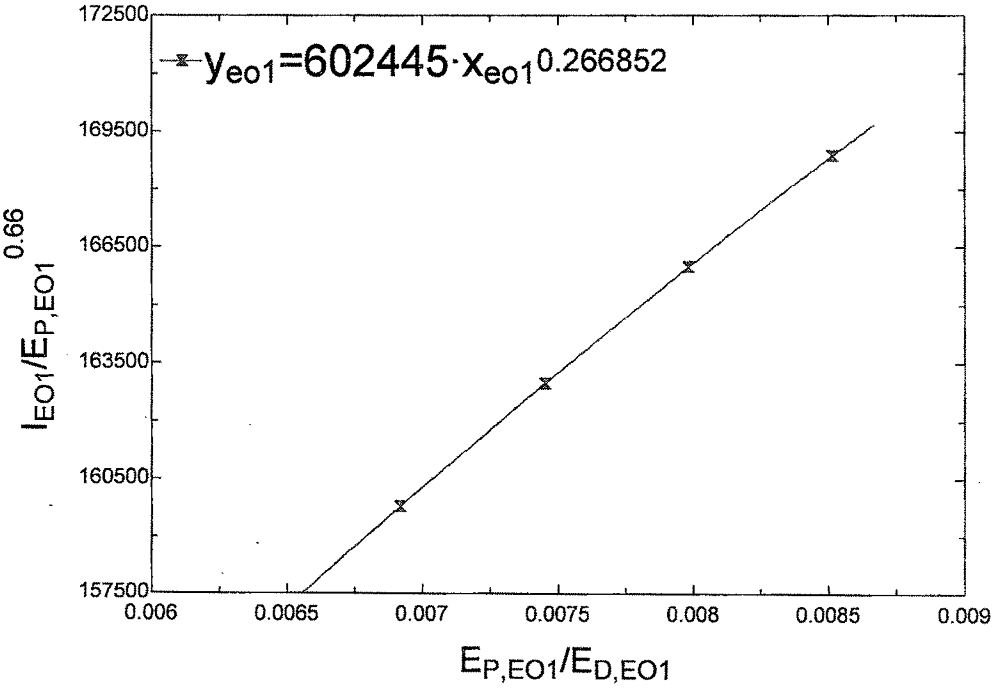

Fig. 5.13 Plot of TCI v/s Exergetic Efficiency for RHX 05

RHX 06

It is a finned tube type heat exchanger. The effectiveness of heat exchanger is considered as decision variable. The value of m_{RHX06} is to be taken as 0.66. Using Table 5.16 and Fig. 5.14, the values of B_{RHX06} and n_{RHX06} are estimated as 79102 and 0.697, respectively.

Table 5.16 Generated Data Using Investment Cost Equation for RHX 06

χ_{RHX06}	$\dot{E}_{P,RHX06}$ kW	$\dot{E}_{D,RHX06}$ kW	$I^{0.8}_{RHX06} / \dot{E}_{P,RHX06}$	$\dot{E}_{P,RHX06} / \dot{E}_{D,RHX06}$
0.50	1.451	4.163	38124	0.3485
0.54	1.555	4.502	37723	0.3454
0.58	1.657	4.857	37368	0.3411
0.62	1.757	5.196	37054	0.3382
0.66	1.856	5.536	36775	0.3352
0.70	1.953	5.892	36527	0.3314
0.74	2.048	6.232	36306	0.3286
0.78	2.141	6.588	36109	0.3249
0.82	2.232	6.944	35934	0.3214
0.86	2.322	7.286	35779	0.3187

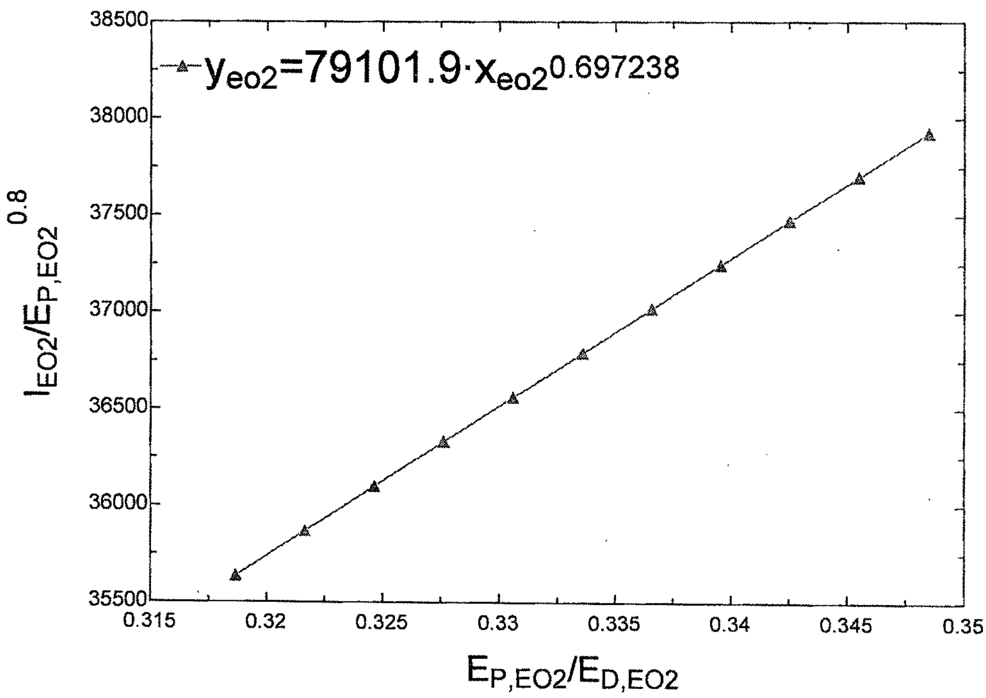

Fig. 5.14 Plot of TCI v/s Exergetic Efficiency for RHX 06

Solution Pump

The efficiency of solution pump is considered as decision variable. For centrifugal pump and motor assembly, the value of m_p is taken as 0.48 [155]. Using Table 5.17 and Fig. 5.15, the values of B_p and n_p are found to be 6462 and 1.003, respectively.

Table 5.17: Generated Data Through Investment Cost Equation for Pump Motor Assembly

η_P	$\dot{E}_{P,P}$ kW	$\dot{E}_{D,P}$ kW	$I_P / \dot{E}_{P,P}^{0.48}$	$\dot{E}_{P,P}/\dot{E}_{D,P}$
0.70	37.99	14.84	16836	2.56
0.72	37.92	13.44	18381	2.82
0.74	37.85	12.12	20210	3.12
0.76	37.78	10.87	22399	3.46
0.78	37.72	9.69	25053	3.90
0.80	37.67	8.56	28319	4.40
0.82	37.61	7.48	32414	5.03
0.84	37.56	6.46	37666	5.81
0.86	37.51	5.49	44595	6.84
0.88	37.46	4.56	54078	8.22

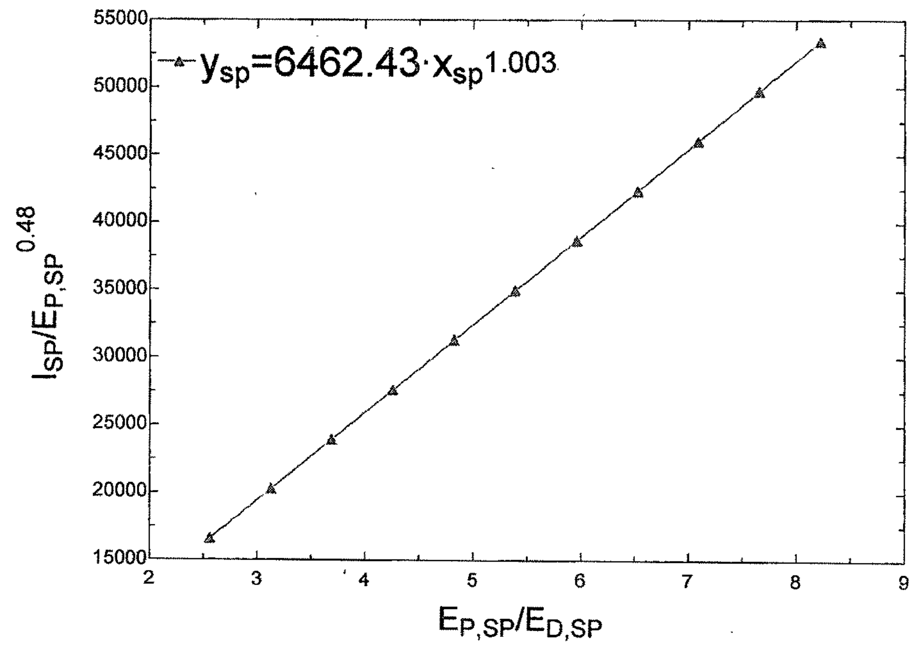

Fig. 5.15 Plot of TCI v/s Exergetic Efficiency for Solution Pump Motor Assembly

Absorber

The absorber temperature is considered as the decision variable and the value of m_a is taken as 0.66. Using Table 5.18 and Fig. 5.16, the values of B_a and n_a are found to be 16053 and 0.071, respectively.

Table 5.18 Generated Data Using Investment Cost Equation for Absorber

T_a °C	$\dot{E}_{p,a}$ kW	$\dot{E}_{D,a}$ kW	$I_a / \dot{E}_{p,a}^{0.66}$	$\dot{E}_{P,a} / \dot{E}_{D,a}$
40	101437	79.76	26584	1272
39	101434	77.76	26655	1304
38	101430	75.64	26726	1341
37	101427	73.4	26797	1382
36	101424	71.02	26868	1428
35	101422	68.52	26939	1480
34	101419	65.88	27010	1539
33	101417	63.11	27080	1607
32	101415	60.21	27150	1684
31	101414	57.17	27220	1774

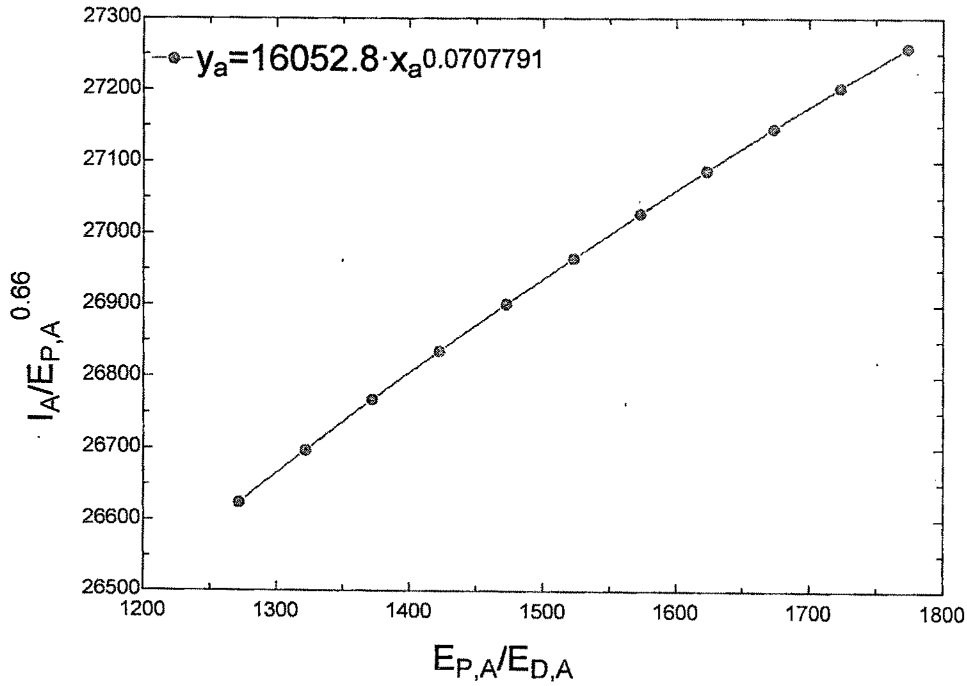

Fig. 5.16 Plot of TCI v/s Exergetic Efficiency for Absorber

Pre-cooler-1

Pre-cooler-1 and 2 are shell and tube heat exchangers. The effectiveness of the heat exchanger is considered as a decision variable and the value of m_{pc1} is taken as 0.54. Using Table 5.19 and Fig. 5.17, the values of B_{pc1} and n_{pc1} are found to be 868652 and 0.0412, respectively.

Table 5.19 Generated Data Using Investment Cost Equation for Pre-cooler-1

χ_{pc1}	$\dot{E}_{p,pc1}$ kW	$\dot{E}_{D,pc1}$ kW	$I_{pc1} / \dot{E}_{p,pc1}^{0.54}$	$\dot{E}_{P,pc1} / \dot{E}_{D,pc1}$
0.36	64.77	261.1	819048	0.248
0.38	72.17	253.7	824368	0.2844
0.4	79.96	245.9	829468	0.3251
0.42	88.15	237.7	834357	0.3708
0.44	96.74	229.2	839047	0.4222
0.46	105.7	220.2	843547	0.4802
0.48	115.1	210.8	847868	0.5462
0.50	124.9	201	852020	0.6216
0.52	135.1	190.8	856012	0.7083
0.54	145.7	180.2	859854	0.8089

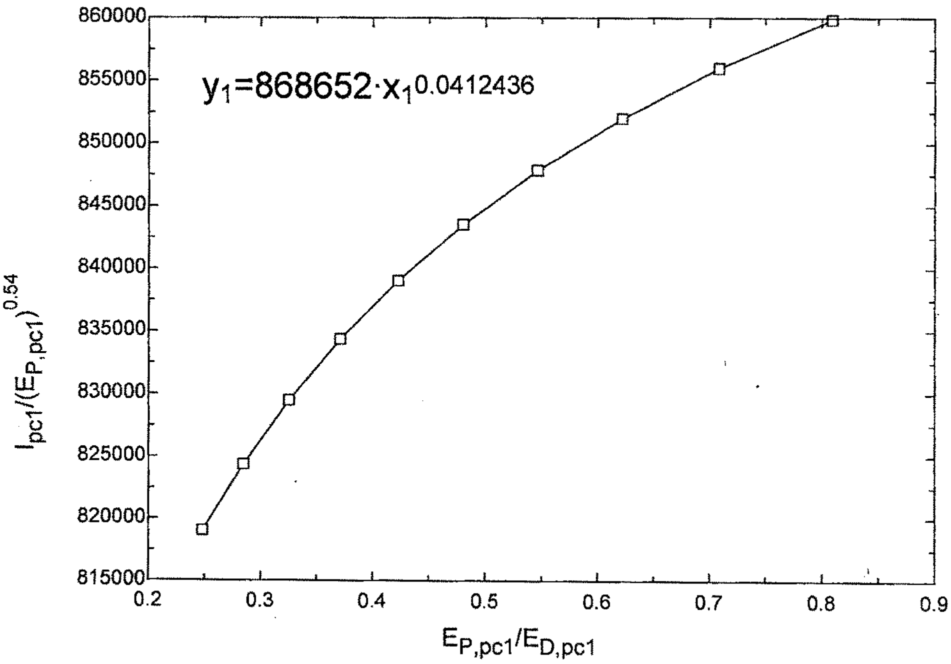

Fig. 5.17 Plot of TCI v/s Exergetic Efficiency for Pre-cooler-1

Pre-cooler-2

The effectiveness of the pre-cooler-2, a shell and tube type heat exchanger is considered as a decision variable and the value of m_{pc2} is taken as 0.54. Using Table 5.20 and Fig. 5.18, the values of B_{pc2} and n_{pc2} are found to be 665723 and 0.01075, respectively.

Table 5.20 Generated Data Using Investment Cost Equation for Pre-cooler-2

χ_{pc2}	$\dot{E}_{p,pc2}$ kW	$\dot{E}_{D,pc2}$ kW	$I_{pc2}/\dot{E}_{p,pc2}^{0.54}$	$\dot{E}_{P,pc2}/\dot{E}_{D,pc2}$
0.38	192.1	416.6	660864	0.4613
0.40	211.1	397.6	661255	0.5308
0.42	230.6	378.1	661937	0.6098
0.44	250.7	358	662825	0.7003
0.46	271.4	337.3	663854	0.8048
0.48	292.8	315.9	664976	0.9267
0.50	314.7	294	666155	1.071
0.52	337.3	271.4	667365	1.243
0.54	360.5	248.2	668586	1.452
0.56	384.3	224.4	669801	1.713

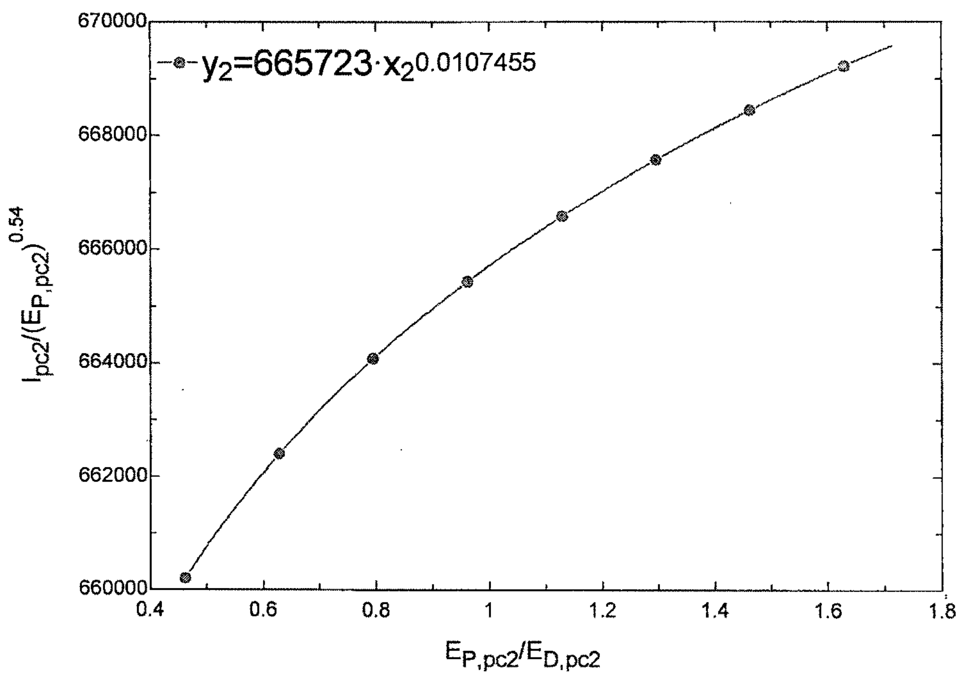

Fig. 5.18 Plot of TCI v/s Exergetic Efficiency for Pre-cooler-2

Table 5.21 summarises the component-wise parameters, B_k , n_k and m_k estimated along with the decision variable.

Table 5.21 Constants of Investment Cost Equation for Components of Brine Chilling Unit

Component	Decision variable	B_k	n_k	m_k
Generator	T_G	226231	0.048	0.66
	t_{brine} (Tc = 36°C)	1.54×10^6	0.0059	0.66
C-E Assembly	t_{brine} (Tc = 38°C)	1.54×10^6	0.0058	0.66
	t_{brine} (Tc = 40°C)	1.54×10^6	0.0057	0.66
SHX	χ_{shx}	2214.01	1.097	0.16
RHX EO5	χ_{EO5}	602445	0.267	0.66
RHX EO6	χ_{EO6}	79101.90	0.697	0.80
Sol. Pump	η_{PM}	6462.40	1.003	0.48
Absorber	T_a	16052.8	0.071	0.66
Pre-cooler-1	χ_{pc1}	868652	0.0412	0.54
Pre-cooler-2	χ_{pc2}	665723	0.01075	0.54

5.3.2 Optimisation Through Case by Case Iterative Procedure for AAVAR system

Optimum values of exergetic efficiency (ε_k^{OPT}), the capital investment (Z_k^{OPT}), the relative cost difference (r_k^{OPT}) and the exergoeconomic factor (f_k^{OPT}) can be calculated using Eqs. 4.37, 4.45, 4.46 and 4.47, respectively. Through an iterative optimization procedure, optimum solution can be achieved, with the help of calculated values of $\dot{C}_{P,tot}, \dot{C}_{D,tot}, \dot{C}_{L,tot}$ and OBF and the guidance provided by the values of $\Delta\varepsilon_k$ and Δr_k, calculated using Eqs. 4.50 and 4.51. A sample calculation using the iterative optimisation of a single component, i.e. generator is given in Appendix E.

Table 5.22 summarizes the results obtained from the case-by-case iteration carried out starting from the base case (base case is the case evaluated using the data of the existing system) to the optimum case. A total of seven iterative cases are presented and the resulting cases are given as cases I to VII out of which the last case, i.e. case VII is found to be the optimum. Each of these cases is obtained through a series of study of positive or negative effects on $\dot{C}_{p,tot}$ and $\dot{C}_{D+L}$ by varying each decision variable. The change in the decision variables are governed by $\Delta\varepsilon_k$ and Δr_k. The details of the case by case iterative procedure for exergoeconomic optimization of AAVAR system is discussed in the following paragraph and the output given in Table 5.22.

Table 5.22 Variables Estimated during the Iterative Optimization of AAVAR system from Base Case to Optimum Case

Variable	Base Case		Case-I		Case -II		Case -III	
T_g	140°C		140°C		140°C		140°C	
T_c	40°C		40°C		40°C		40°C	
T_a	40°C		40°C		40°C		40°C	
T_e	-20°C		-20°C		-20°C		-20°C	
η_p	90%		90%		90%		85%	
χ_{SHX}	0.80		0.85		0.85		0.85	
χ_{RHX05}	0.49		0.49		0.49		0.49	
χ_{RHX06}	0.80		0.80		0.85		0.80	
Component	$\Delta\varepsilon(\%)$	$\Delta r(\%)$	$\Delta\varepsilon(\%)$	$\Delta r(\%)$	$\Delta\varepsilon(\%)$	$\Delta r(\%)$	$\Delta\varepsilon(\%)$	$\Delta r(\%)$
Generator	-4.37	28.32	-8.94	121.60	-8.99	88.72	-8.95	121.30
Cond Evap Assly.	-70.88	353.50	-70.88	382.50	-70.89	383.20	-70.89	388.20
SHX	-30.03	4619.00	-25.42	3877.00	-25.41	4371.00	-25.40	3879.00
RHX05	-98.45	10684.00	-98.45	9338.00	-98.24	5490.00	-98.45	9339.00
RHX06	-70.62	1335.00	-70.64	3200.00	-70.91	732.20	-70.63	3201.00
Solution Pump	-3.47	3168.00	-3.44	3184.00	-3.44	1159.00	-8.22	3476.00
Absorber	-0.23	-68.03	-0.20	-53.37	-0.19	-91.85	-0.20	-55.50
$\dot{C}_{L,tot}$	1960 ₹/hr		2009 ₹/hr		2014 ₹/hr		2010 ₹/hr	
$\dot{C}_{D,tot}$	12820 ₹/hr		13142 ₹/hr		13164 ₹/hr		13164 ₹/hr	
$\dot{C}_{P,tot}=\dot{C}_{P,exp}+\dot{C}_{P,pc1}+\dot{C}_{P,pc2}$	(6660 + 1626 + 6713) ₹/hr		(7020 +1556+3413) ₹/hr		(7085+1556+3413) ₹/hr		(7074+1556+3413) ₹/hr	
$OBF=\dot{C}_P+\dot{C}_{L,tot}+\dot{C}_{D,tot}$	6660+1960+12820 = 21440 ₹/hr		7020+2009+13142 = 22171 ₹/hr		7085+2014+13164 = 22263 ₹/hr		7074+2010+13164 = 22248 ₹/hr	

Table 5.22 (Continued)

Variable	Case –IV		Case -V		Case -VI		Case -VII	
T_g	140°C		140°C		142°C		142°C	
T_c	38°C		38°C		38°C		38°C	
T_a	38°C		38°C		38°C		38°C	
T_e	-18°C		-17°C		-17°C		-17°C	
η_p	0.85		0.85		0.85		0.85	
χ_{SHX}	0.85		0.85		0.85		0.85	
χ_{RHX05}	0.49		0.49		0.49		0.47	
χ_{RHX06}	0.80		0.80		0.80		0.78	
Component	$\Delta\varepsilon(\%)$	$\Delta r(\%)$	$\Delta\varepsilon(\%)$	$\Delta r(\%)$	$\Delta\varepsilon(\%)$	$\Delta r(\%)$	$\Delta\varepsilon(\%)$	$\Delta r(\%)$
Generator	-8.60	76.65	-8.54	127.90	-7.55	75.55	-7.19	105.60
Cond Evap Assly.	-69.92	232.20	-69.42	174.80	-69.44	196.90	-69.50	168.20
SHX	-26.37	4791.00	-26.38	4669.00	-26.42	4585.00	-26.42	4590.00
RHX05	-97.66	5699.00	-97.96	6117.00	-97.96	590.40	-98.54	5583.00
RHX06	-73.80	2675.00	-73.12	2577.00	-76.39	273.60	-72.98	2584.00
Solution Pump	-8.26	1860.00	-8.23	4230.00	-8.23	4229.00	-8.23	4188.00
Absorber	-0.23	-95.18	-0.25	-62.93	-0.25	91.08	-0.23	-88.97
$\dot{C}_{L,tot}$	1803 ₹/hr		1727 ₹/hr		1721 ₹/hr		1716 ₹/hr	
$\dot{C}_{D,tot}$	11802 ₹/hr		11300 ₹/hr		11266 ₹ /hr		11238 ₹/hr	
$\dot{C}_{P,tot}=\dot{C}_{P,evp}+\dot{C}_{P,pc1}+\dot{C}_{P,pc2}$	(5512+1556+3413) ₹/hr		(4932 + 1556+3413) ₹/hr		(4892 +1556+3413) ₹/hr		(4853 +1556+3413) ₹/hr	
$OBF=\dot{C}_P+\dot{C}_{L,tot}+\dot{C}_{D,tot}$	5512+1803+11802 = 19117 ₹/hr		4932+1727+11300 = 17959 ₹/hr		4892+1721+11266 = 17879 ₹/hr		4853+1716+11238 = 17807 ₹/hr	

From Base Case to Case-I

The high value of Δr_{RHX05} in the base case suggests that the product cost of RHX 05 is very high. It also suggests that the effectiveness of RHX 05 should be increased. However, further increase of effectiveness is not possible for RHX 05, as it is already the maximum due to flow condition. The next highest product cost is for SHX. Therefore, the effectiveness of SHX is increased from 0.80 to 0.85. This resulted in the decrease of product cost of SHX. However, it is found that the change has adverse effect on the product cost of RHX 06 and generator. Nevertheless, it is now clear that an increase in effectiveness of SHX may be considered for the next set of the iteration.

From Case-I to Case-II

The next highest product cost is observed for RHX 06 due to the high value of Δr_{RHX06}. To reduce the product cost for RHX06, its effectiveness is increased from 0.80 to 0.85. Although, the cost of final product is increased, it is seen that there is no major adverse effect on the performance of the other component. Therefore, effectiveness of RHX06 is not considered as a variable for next iteration.

From Case-II to Case-III

During the exergoeconomic evaluation, it was observed that the investment cost of the solution pump should be reduced. By reducing the efficiency of the pump from 90% to 85%, it is seen that the cost of final product is reduced.

From Case-III to Case-IV

The next highest product cost is observed with condenser evaporator assembly from the value of Δr_{CE}. It may be because of high exergy destruction associated with the processes in the assembly. To reduce the exergy destruction, condenser temperature can be decreased and evaporator temperature can be increased to reduce the temperature difference between two fluids in the heat exchangers. When the temperature of condenser is decreased from 40°C to 38°C and temperature of evaporator is increased from -20°C to -18°C, it is seen the production cost of condenser evaporator assembly is reduced and thereby the cost of final product is decreased.

From Case-IV to Case-V

Considering the condenser temperature and evaporator temperature as variables for the next iteration, it is observed that the increase in evaporator temperature gives favourable result but the reduction in condenser temperature does not. So the new evaporator temperature is considered as variable for next iteration.

From Case-V to Case-VI

The component having next highest production cost is generator as illustrated by the value of Δr_G. The production cost can be reduced by decreasing the exergy destruction in the generator. It can be achieved by increasing the generator temperature. The generator temperature is increased from 140°C to 142°C which results in reduction in the production cost of generator and that of overall system.

From Case-VI to Case-VII

The decrease in the effectiveness of RHX 05 from 0.49 to 0.47 and that for RHX 06 from 0.80 to 0.78 gives reduction in the cost of final product.

5.3.3 Optimisation through Iterative Procedure for Pre-coolers 1 and 2

Pre-cooler-1 and pre-cooler-2 are considered as independent components as the variation in the controlling parameter of both the pre-cooler do not affect the performance of AAVAR system. Therefore the optimization of both the pre-coolers can be carried out independently.

Table 5.23 shows the effect of variation of effectiveness on the investment cost and the product cost for pre-cooler-1. With increase in the effectiveness of the pre-cooler-1, the cost of product will increase but the investment cost will decrease. With optimum condition, the temperature of brine, coming out of pre-cooler-1, will be 13.27°C which is considered as the input temperature for pre-cooler-2. Fig. 5.19 shows that the total cost of product is minimum at effectiveness $\chi_{pc1} = 0.43$ and corresponding product cost is 1556 ₹/hr. The same value of product cost is considered in the final iteration for the overall optimization performed above. Following the same procedure for pre-cooler-2, the variation of product cost and investment cost with respect to effectiveness for pre-cooler-2 is shown in Table 5.23 and Fig. 5.20. Table 5.23 shows that the optimum point can be achieved at $\chi_{pc2} = 0.47$ with the outlet brine temperature -0.5°C with product cost 3413 ₹/hr can be achieved.

Table 5.23 Effect of Effectiveness on Investment Cost for Pre-cooler-1

$T_{br,o}$ °C	χ_{pc1}	Q_{pc1} kW	$C_{p,pc1}$ ₹/hr	$\dot{Z}_{pc1}$ ₹/hr	$(C_{p,pc1} + \dot{Z}_{pc1})$ ₹/hr
15.0	0.3648	3771	1590	77.92	1668
14.5	0.3836	3965	1577	83.06	1660
14.0	0.4024	4158	1567	88.37	1655
13.5	0.4212	4352	1559	93.83	1653
13.0	0.44	4545	1553	99.48	1653
12.5	0.4588	4739	1549	105.3	1655
12.0	0.4776	4932	1547	111.4	1658
11.5	0.4964	5125	1545	117.6	1663
11.0	0.5152	5318	1545	124.1	1669
10.5	0.534	5511	1546	130.9	1677
10.0	0.5528	5704	1547	137.9	1685

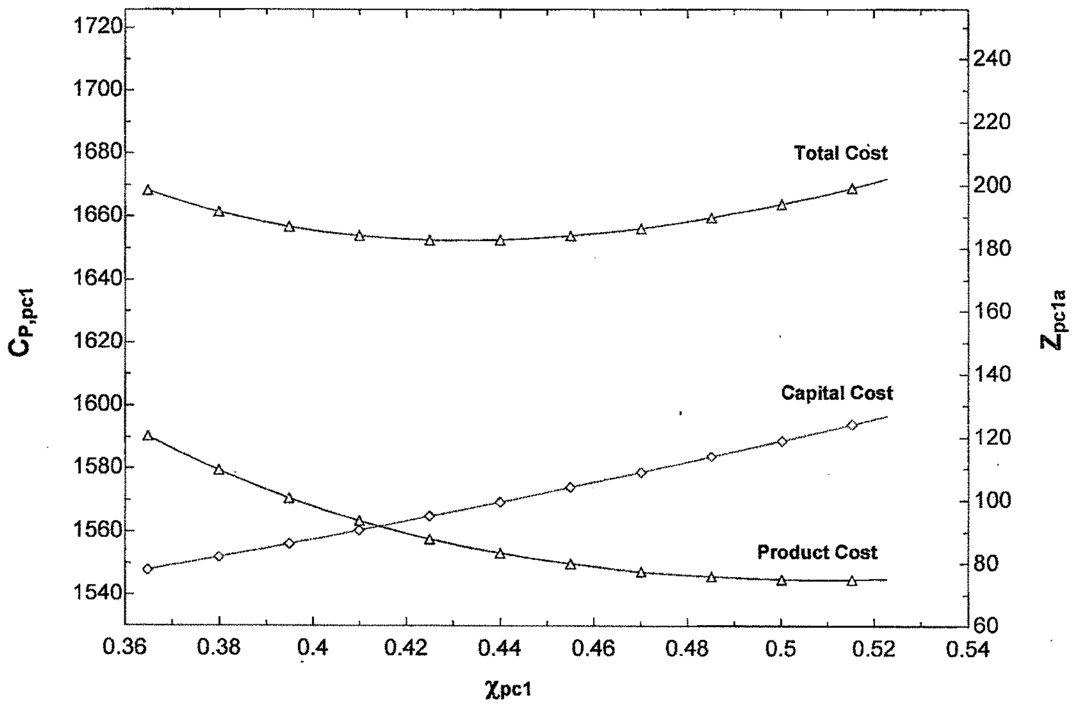

Fig. 5.19 Optimum Product Cost for Pre-cooler-1

Table 5.24 Effect of Effectiveness on Investment Cost for Pre-cooler-2

$T_{br,o}$ °C	χ_{pc2}	Q_{pc2} kW	$\dot{Z}_{pc2}$ ₹/hr	$C_{p,pc2}$ ₹/hr	$(C_{p,pc2} + \dot{Z}_{pc2})$ ₹/hr
8.0	0.1747	1929	135.8	5851	5986
7.0	0.2096	2314	166.4	5066	5232
6.0	0.2445	2699	198.2	4553	4751
5.0	0.2795	3083	231.6	4198	4430
4.0	0.3144	3467	266.6	3944	4210
3.0	0.3493	3850	303.4	3757	4060
2.0	0.3843	4233	342.2	3618	3961
1.0	0.4192	4616	383.3	3516	3899
0.0	0.4542	4998	426.8	3441	3868
-1.0	0.4891	5380	473.3	3389	3862
-2.0	0.524	5762	522.9	3355	3878
-3.0	0.559	6143	576.4	3337	3914

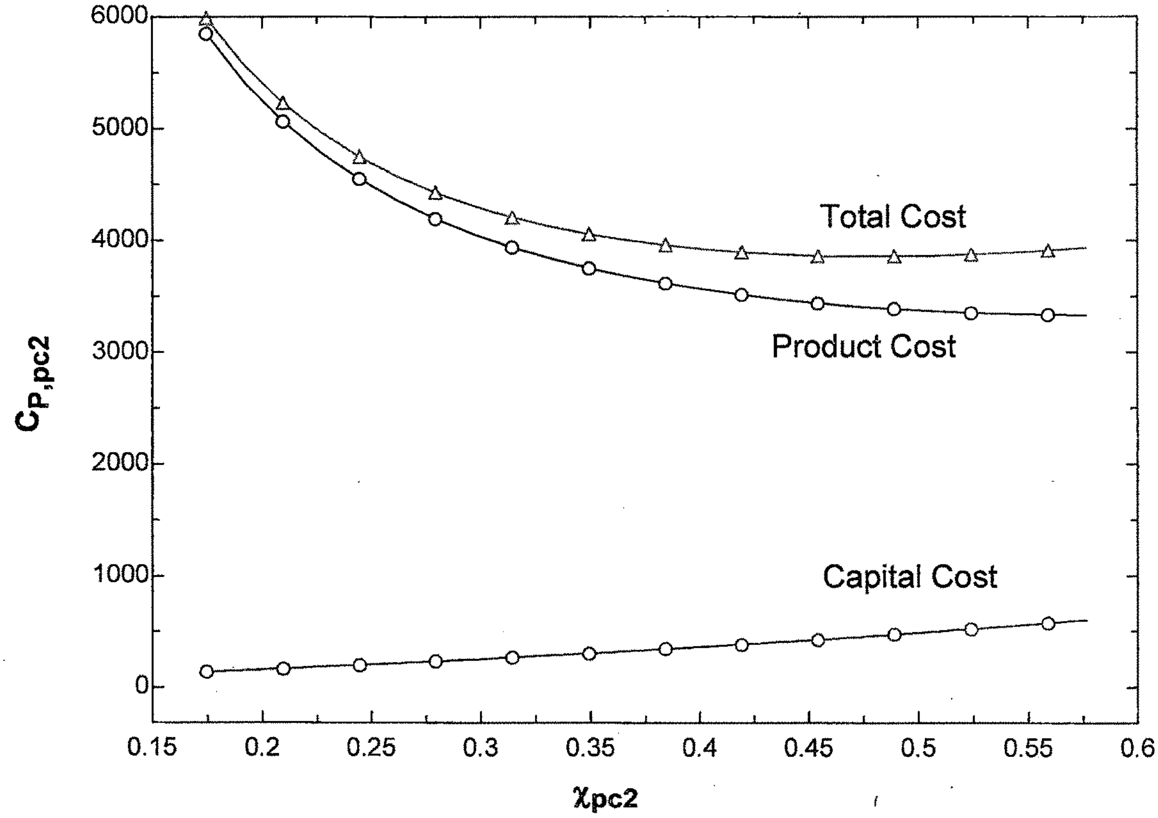

Fig. 5.20 Optimum Product Cost for Pre-cooler-2

5.3.4 Results and Discussions

In exergoeconomic optimization of brine chilling unit, the AAVAR system and both pre-coolers are optimized separately. The optimized pre-cooler-1 has effectiveness of 0.43 and corresponding product cost is 1556 ₹/hr whereas, the effectiveness and product costs of pre-cooler-2 are 0.47 and 3413 ₹/hr, respectively. It is observed that the product cost for pre-cooler-2 is quite high compared to that for pre-cooler-1, though the performance of pre-cooler-2 is better than that of pre-cooler-1. This is because of the very large O&M cost for pre-cooler-2 (Refer Table 5.9). It is suggested to reduce the O&M cost by reducing the heat transfer area for pre-cooler-2. The optimized AAVAR system is having the cost of 4853 ₹/hr for the cooling generated at evaporator of the system. Table 5.25 gives a comparative study of the final cost optimal configuration with the base case. The overall thermoeconomic cost of the product (chilled brine) is decreased by about 27.13 % (6660 ₹/hr to 4853 ₹/hr) with corresponding 12.76 % decrease (1.96 ₹/MJ to 1.71 ₹/MJ) in the fuel cost results from the reduction in consumption of fuel. The cost of exergy destruction is also decreased by 12.34 % and that of exergy loss is decrease by 12.45 %. These cost reduction is accompanied by the increase in the investment cost of solution heat exchanger and reduction in the investment cost of solution pump, RHX 05 and RHX 06. Improvement in the system performance can be realized by the increase in the exergetic efficiency by 13.04 % and increase in the COP by 11.9 %.

Table 5.25 Comparison between the Base Case and the Optimum Case

Properties	Base Case	Optimum Case	% Variation
Fuel Cost $\dot{C}_{F,tot}$	1.96 ₹ /MJ	1.71 ₹ /MJ	-12.76
Product Cost $\dot{C}_{P}$	6660 ₹ /hr	4853 ₹/hr	-27.13
Loss $\dot{C}_{L,tot}$	1960 ₹/hr	1716 ₹/hr	-12.45
Destruction $\dot{C}_{D,tot}$	12820 ₹/hr	11238 ₹/hr	-12.34
Exergetic Efficiency ε%	23 %	26 %	13.04 %
COP	0.42	0.47	11.90 %