CHAPTER 4

EXERGY ANALYSIS OF COMBINED RRVPC AND SINGLE EFFECT H_2O–LiBr VARS

4.1 Introduction

Exergy analysis based on second law of thermodynamics is a powerful tool for evaluating inefficiency of thermodynamic processes and energy systems. First law based energy analysis alone is not sufficient to evaluate some features of energy resource utilization as it provides only the quantitative measurement ignoring completely the qualitative aspect of it. Second law deals with energy quality and provides the framework for evaluating irreversible losses occurring in thermodynamic processes. It also offers engineers a plenty of scope for improvement of system operations.

In energy analysis, system performance of a VARS is usually evaluated in terms of COP and thermal load in various system components using different types of solution pairs. Some parametric studies evaluate system performance under various operating conditions of component operating temperatures, effectiveness of solution, refrigerant and solution–refrigerant heat exchangers, cooling capacity etc. Similarly, in energetic performance analysis of a VPC based thermal power plant, the system performance is generally analyzed in terms of power output and energy efficiency based on variation of fuel quality and other operating parameters such as BP, condenser pressure, STIT, number of feed water heaters used, FFR and AFR etc. In case of CPC systems, energy analysis involves determination of power, cooling, energy efficiency of power cycle, COP of cooling system, overall energy utilization factor (EUF) etc. However, as stated earlier, first law based energy analysis alone is not sufficient to evaluate complete details of energy resource utilization. It is the second law based exergy analysis that provides the complete details of energy resource utilization with better insight to the system operations. Exergy analysis is must if someone desires to evaluate the source of inefficiency and irreversible losses occurring in various system components. Moreover, system analysis together with the help of energy and exergy gives a complete overview of the system characteristics.

In chapter 3, the detail thermodynamic model and analysis of the combined RRVPC and H_2O–LiBr VARS was presented from the first law point of view. Net power and efficiency of the RRVPC; COP of the H_2O–LiBr VARS were determined under various operating conditions of FFR to the boiler furnace, BP, VARS cooling capacity and component's operating temperatures. Further a comparative analysis of performance was provided between the combined plant and the plant without VARS quantifying the performance variation due to VARS integration. Thermodynamic analysis on such a cogeneration system involving combination of a steam based power cycle and a H_2O–LiBr was not available in literature prior to this work. The same CPC as described in section 3.2 (Fig. 3.1) of Chapter 3 is analyzed from the second law point of view in this chapter. Important exergetic performance parameters of the proposed combined plant including irreversibility in various system components are evaluated with the help of a numerical code developed in C language and presented along with the first law based performance parameters.

4.2. Assumptions

The coal used as boiler fuel in the topping RRVPC has the same composition as mentioned in section 3.3 of Chapter 3.Other assumptions which were considered and presented in Chapter 3 for energy based thermodynamic modeling of the CPC system are also more or less same.

In the exergy based modelling also, complete combustion of coal is assumed with flue gas comprising of only carbon–di–oxide (CO_2), sulfur–di–oxide (SO_2), water vapor $(H_2O)$and nitrogen. It is assumed that fuel and air bound oxygen is just sufficient to completely oxidize the combustible elements in the fuel and hence no oxygen in the product flue gas. Ash in the flue gas is also neglected. The complete combustion equations used for determination of flue gas composition and the combustion air flow rate were explained in Chapter 3. Fuel flow rate supplied to the boiler furnace and boiler pressure is specified as model input parameter. Steam generated in the boiler is assumed to be superheated at 500°C. The OWH pressure is determined from the condition of maximum efficiency [1] as described in section 3.3 of Chapter 3.

Steady flow assumptions have been made neglecting the kinetic and potential energy effects. It is assumed that the reference environment has a temperature of 298.15

K, pressure of 1.01325 bar and relative humidity of 50%. Furthermore, the reference environment is considered a mixture of perfect gases with the following composition on a molar basis: N_2, 75.67%; O_2, 20.35%; CO_2, 0.03%; H_2O, 3.12%; other gases, 0.83%**.** Fuel thermo–mechanical exergy is considered to be zero at boiler inlet. It is assumed that the state of air entering the boiler is in chemical equilibrium with the reference environment and its chemical contribution to exergy is equal to zero. The various parameters assumed for simulation of combined system components are similar to those of Table 3.1 presented in chapter 3.

4.3 Energy and exergy based thermodynamic modelling

The thermodynamic model developed for energy based performance simulation of the combined RRVPC and single effect H_2O–LiBr VARS was presented and described in detail in Chapter 3. The exergy based thermodynamic model of the combined system will mainly be described in the following sections. However, since, the analysis of the combined system would be provided both from the first (energy) and second law (exergy) point of view, therefore, the energy based thermodynamic model which was presented in Chapter 3 will also be briefly highlighted in this chapter along with the exergy based thermodynamic model.

4.3.1 Toping RRVPC

As mentioned earlier in Chapter 3 (section 3.4.1), first the specific enthalpy and entropy at all the salient points of the Rankine cycle based RRVPC are calculated. Steady flow energy equation (SFEE) is applied for finding work and heat transfer terms associated with various system components. The pumping power calculation procedure for the CT side pumps (CTP) is also the same as described in section 3.4.3 of Chapter 3. The fuel (coal) mass flow rate $(\dot{m}_f)$and its composition are specified as model input parameters. Based on the fuel composition and assuming that it is complete fuel combustion, next, the numbers of moles of the components in the product gases are determined. The fuel's lower heating value (LHV_f) is calculated using the molar coefficients and the standard molar specific enthalpy of devaluation of product and reactant species. Next, the quantity of energy lost with the boiler leaving flue gas $(\dot{E}_{fg})$at the given exhaust temperature $(T_g)$is calculated using the values of $\dot{m}_f$ and the sum of enthalpy difference of all the flue gas components with respect to their enthalpy values at

T_g and the reference temperature (T_0) .Using the values of fuel energy input $(\dot{m}_f \times LHV_f)$and loss of energy with flue gas$(\dot{E}_{fg})$, next an energy balance is applied to the boiler control volume to calculate the steam generation rate $(\dot{m}_s)$in the boiler.

Chemical exergy of fuel (coal) is calculated using the following equation [2]

$$\dot{E}x_{ch,f} = \frac{\dot{m}_f}{100}\left[\left\{\left(LHV_f + 2442\frac{H_2O}{100}\right)\phi + 9417\frac{S}{100}\right\}\right] \quad (4.1)$$

where, $\phi = 1.0437 + 0.1882\frac{H}{C} + 0.061\frac{O}{C} + 0.0404\frac{N}{C}$ (4.2)

Fuel thermo mechanical exergy is assumed to be zero while the thermo mechanical exergy of incoming air stream is calculated using the following equation [3]. Chemical exergy of air is also neglected.

$$ex_{tm,a} = \dot{m}_{a,dry}\left[\left(C_{pa} + \omega_a C_{pv}\right)\left(T_a - T_0 - T_0 \ln\frac{T_a}{T_0}\right) + R_a T_0\left\{\frac{(1+1.608\omega_a)\ln(1+1.608\omega_0)}{1+1.608\omega_a} + 1.608\omega_a \ln\frac{\omega_a}{\omega_0}\right\}\right] \quad (4.3)$$

where, T_a is the dry bulb temperature (DBT) of moist air, ω_a is the specific humidity at a given DBT and relative humidity (RH), $\omega_0$is the specific humidity at 25°C and 50% RH. $C_{pa}$and$C_{pv}$are the specific heats of dry air and water vapour which are taken as 1.005 kJ/kgK and 1.872 kJ/kg.K respectively. R_a is the characteristic gas constant and its value for air is 0.287 kJ/kgK. The above equation is also used for calculating thermo mechanical exergy of humid air stream at inlet and exit of the CT as well as the AC apparatus.

The energy and exergy efficiencies of the power cycle and the energy utilization factor (EUF) of the combined power and cooling system are determined using the following equations.

$$\eta_I = \frac{\dot{m}_s\left(W_{ST} - W_{pump}\right) - \dot{m}_{w,CTpump}W_{CTpump}}{\dot{m}_f LHV_f} \quad (4.4)$$

$$\eta_{II} = \frac{\dot{m}_s\left(W_{ST} - W_{pump}\right) - \dot{m}_{w,CTpump} W_{CTpump}}{\dot{E}x_{ch,f} + \dot{E}x_{tm,a}} \tag{4.5}$$

$$EUF = \frac{\dot{m}_s\left(W_{ST} - W_{pump}\right) - \dot{m}_{w,CTpump} W_{CTpump} + \dot{Q}_E}{\dot{m}_f LHV_f} \tag{4.6}$$

The irreversibility at various components of topping cycle has been calculated as follows:

Boiler irreversibility:

$$\dot{I}_{boiler} = \dot{E}x_{ch,f} + \dot{E}x_{tm,a} - \dot{E}x_{fg} - \dot{m}_s\left[\left(h_1 - h_{17}\right) + (1-x)\left(h_3 - h_2\right) - T_0\left(s_1 - s_{17}\right) + (1-x)\left(s_3 - s_2\right)\right] \tag{4.7}$$

For calculating irreversibility of the flue gas $\left(\dot{I}_{fg}\right)$, both the chemical and thermo–mechanical exergy are considered. Molar specific chemical exergy of flue gas is calculated from the equation stated below.

$$\dot{E}x_{ch,fg} = RT_0 \sum_i \dot{n}_i \ln\left(\frac{y_i}{y_i^0}\right) \tag{4.8}$$

where, $\dot{n}_i$ is the molar flow rate, y_i and y_i^0 are the mole fractions of the species i in the flue gas product and the reference environment respectively.

Thermo–mechanical exergy of the flue gas stream is found out using Eq. (4.9).

$$\dot{E}x_{tm,fg} = \sum_i \dot{n}_i\left[\bar{h}_i(T) - \bar{h}_i(T_0) - T_0\left(\bar{s}_i^{\,0}(T) - \bar{s}_i^{\,0}(T_0)\right) - RT_0 \ln\frac{p}{p_0}\right] \tag{4.9}$$

Total exergy of flue gas is sum of the chemical and the thermo–mechanical exergy

$$\dot{I}_{fg} = \dot{E}x_{ch,fg} + \dot{E}x_{tm,fg} \tag{4.10}$$

Turbine irreversibility:

$$\dot{I}_{ST} = \dot{m}_s T_0\left[\left(s_2 - s_1\right) + (1-x)\left(s_4 - s_3\right) + (1-x-y)\left(s_5 - s_4\right) + (1-x-y-z)\left(s_6 - s_5\right)\right] \tag{4.11}$$

Power cycle condenser (PCC) irreversibility:

$$\dot{I}_{PCC} = T_0\left[\dot{m}_{w,PCC}C_{pw}\log\left(\frac{T_{wo}}{T_{wi}}\right) + \dot{m}_s(1-x-y-z)(s_7-s_6)\right] \tag{4.12}$$

Irreversibility in BFP1:

$$\dot{I}_{BFP1} = \dot{m}_s T_0 (1\text{ - x - y - z})(s_8\text{-}s_7) \tag{4.13}$$

Irreversibility in BFP2:

$$\dot{I}_{BFP2} = \dot{m}_s T_o (1-y)(s_{10}-s_9) \tag{4.14}$$

Irreversibility in BFP3:

$$\dot{I}_{BFP3} = \dot{m}_s T_o y(s_{13}-s_{12}) \tag{4.15}$$

Irreversibility in BFP4:

$$\dot{I}_{BFP4} = \dot{m}_s T_o x(s_{16}-s_{15}) \tag{4.16}$$

Total BFP irreversibility:

$$\dot{I}_{BFP} = \dot{I}_{BFP1} + \dot{I}_{BFP2} + \dot{I}_{BFP3} + \dot{I}_{BFP4} \tag{4.17}$$

Irreversibility in OWH:

$$\dot{I}_{OWH} = \dot{m}_S T_O[(1-x)s_{12} - ys_4 - (1-x-y)s_{11}] \tag{4.18}$$

Irreversibility in CWH:

$$\dot{I}_{CWH} = \dot{m}_S T_O[x(s_{15}-s_2) + (1-x)(s_{14}-s_{13})] \tag{4.19}$$

Irreversibility in MC1:

$$\dot{I}_{MC1} = \dot{m}_s T_o[s_{11} - (1-x-y-z)s_8 - zs_{10}] \tag{4.20}$$

Irreversibility in MC2:

$$\dot{I}_{MC2} = \dot{m}_s T_o[(1-x)(s_{17}-s_{14}) + x(s_{17}-s_{16})] \tag{4.21}$$

In the above equations, x, y and z are the fractions of steam extracted per kg of steam for the CWH, OWH and the VARS generator respectively. Irreversibility calculations for the CT, CTPs and the AC apparatus depends upon the working of the bottoming VARS, hence these are shown in the following section along with the irreversibility calculations of VARS components.

4.3.2 H_2O–LiBr VARS

For the H_2O–LiBr VARS, temperature dependent concentration of the strong and weak solution of the refrigerant is known [4]. Thermodynamic properties such as specific enthalpy, entropy of the refrigerant (water) both in liquid and vapour state at various pressures and temperature are determined from International Associations for the properties of water and steam (IAPWS) formulation 1997 [5]. Similarly the thermodynamic properties of H_2O–LiBr solutions at various temperatures and concentration are calculated using the correlations proposed by Patek and Klomfar [6].

From known evaporator cooling load (CL), the mass flow rate of refrigerant is determined using the following equation

$$\dot{m}_{H_2O} = \frac{\dot{Q}_E}{h_4' - h_3'} \tag{4.22}$$

Strong and weak solution mass flow rates are calculated using equations taken from the Ref. [4]. Thermal load in the generator, absorber and condenser are calculated. The amount of steam required to be extracted from the steam turbine of the power cycle as heat source for the VARS generator is calculated using the following equation.

$$\dot{m}_{s,extracted} = \frac{\dot{Q}_G}{h_5 - h_9} \tag{4.23}$$

Cooling water flow rate through the evaporator/AC apparatus, absorber and the VARS condenser are determined from heat balance applied to these devices. The actual COP, maximum possible COP and exergetic efficiency of the VARS are defined as follows:

$$COP = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_p}, \ W_p \text{ be the solution pump work.} \tag{4.24}$$

$$COP_{\max} = \left(\frac{T_G - T_A}{T_G} \right) \left(\frac{T_E}{T_C - T_E} \right) \tag{4.25}$$

$$\text{VARS exergetic efficiency} = \frac{\left(\dot{E}x_{water,Eo} - \dot{E}x_{water,Ei} \right)}{\left(\dot{E}x_5 - \dot{E}x_9 \right)} \tag{4.26}$$

Exergetic efficiency of the combined power and cooling system is defined by the following equation.

$$\eta_{II,CS} = \frac{\dot{m}_s \left(W_{ST} - W_{pump} \right) - \dot{m}_{w,CTpump} W_{CTpump} + \dot{E}x_{water,Eo} - \dot{E}x_{water,Ei}}{\dot{E}x_{ch,f} + \dot{E}x_{tm,a} + \dot{E}x_5 - \dot{E}x_9} \tag{4.27}$$

For analysis of the A/C apparatus, specific humidity and specific enthalpy of moist air (per kg of dry air) are calculated. The AC apparatus exit water temperature of '$T_{w,o}$' is calculated from energy balance. The water from the power cycle condenser and the condenser, absorber and AC apparatus of the VARS, all goes to MC3. The temperature of the mixed water stream is calculated as follows:

$$t_{mix,out} = \left[\frac{\dot{m}_{w,PCC} t_{w,PCCo} + \dot{m}_{w,C} t_{w,Co} + \dot{m}_{w,AC} t_{w,ACo} + \dot{m}_{w,A} t_{w,Ao}}{\dot{m}_{w,PCC} + \dot{m}_{w,C} + \dot{m}_{w,AC} + \dot{m}_{w,A}} \right] \tag{4.28}$$

The irreversibility at various components in VARS has been calculated as follows:

Irreversibility in generator:

$$\dot{I}_G = \dot{m}_{ss} ex'_7 - \dot{m}_{ws} ex'_8 - \dot{m}_r ex'_1 + z\dot{m}_s \left[(h_5 - h_9) - T_o (s_5 - s_9) \right] \tag{4.29}$$

In this equation, $ex' = (h' - h^0) - T_o (s' - s^0)$ is the specific exergy of the flow stream.

Irreversibility in evaporator:

$$\dot{I}_E = \dot{m}_r (ex'_3 - ex'_4) + \dot{m}_{w,E} C_{p,w} \left[(t_{w,Ei} - t_{w,Eo}) - T_0 \log \left(\frac{T_{w,Ei}}{T_{w,Eo}} \right) \right] \tag{4.30}$$

where, $\dot{m}_{w,E}$ is water flow rate through evaporator, $t_{w,Ei}$ and $t_{w,Eo}$ are temperatures of water at evaporator inlet and outlet.

Irreversibility in VARS condenser:

$$\dot{I}_C = \dot{m}_r \left(ex'_1 - ex'_2\right) + \dot{m}_{w,C} C_{p,w} \left[\left(t_{w,Ci} - t_{w,Co}\right) - T_0 \log\left(\frac{T_{w,Ci}}{T_{w,Co}}\right)\right] \quad (4.31)$$

where, $\dot{m}_{w,c}$ is water flow rate through condenser, $t_{w,Ci}$, $t_{w,Co}$ are water temperatures at VARS condenser inlet and outlet.

Absorber irreversibility is:

$$\dot{I}_A = \dot{m}_r ex'_4 + \dot{m}_{ws} ex'_{10} - \dot{m}_{ss} ex'_5 + \dot{m}_{w,A} C_{p,w} \left[\left(t_{w,Ai} - t_{w,Ao}\right) - T_0 \log\left(\frac{T_{w,Ai}}{T_{w,Ao}}\right)\right] \quad (4.32)$$

where, $\dot{m}_{w,A}$ is water mass flow rate through absorber, $t_{w,Ai}$ and $t_{w,Ao}$ are water temperatures at absorber inlet and outlet.

Solution heat exchanger (SHE) irreversibility:

$$\dot{I}_{SHE} = \dot{m}_{ws} \left[\left(h'_8 - h'_9\right) - T_o \left(s'_8 - s'_9\right)\right] - \dot{m}_{ss} \left[\left(h'_7 - h'_6\right) - T_0 \left(s'_6 - s'_7\right)\right] \quad (4.33)$$

AC apparatus irreversibility is calculated as given below:

$$\dot{I}_{AC} = \left(\dot{E}x_{ai} - \dot{E}x_{ao}\right) - \dot{m}_{w,AC} \left[C_{p,w}\left(t_{w,ACo} - t_{w,ACi}\right) - T_o \left(s_{w,ACo} - s_{w,ACi}\right)\right] \quad (4.34)$$

where, $\dot{m}_{w,AC}$ is water mass flow rate through AC apparatus, $t_{w,aci}$ and $t_{w,aco}$ are water temperatures at AC apparatus inlet and outlet. Exergy of humid air $\left(\dot{E}x_a\right)$ is calculated using equation taken from [3] assuming 50% relative humidity of standard reference environment as stated earlier.

Irreversibility in mixing chamber 3: $\dot{I}_{MC3} = \dot{E}x_{wi} - \dot{E}x_{wo}$ (4.35)

CT irreversibility:

$$\dot{I}_{CT} = \left(\dot{m}_{w,PCC} + \dot{m}_{w,C} + \dot{m}_{w,A} + \dot{m}_{w,E}\right) \left[C_{p,w}\left(t_{mixo} - 25.0\right) - T_o \log\left(\frac{t_{mixo} + 273.15}{298.15}\right)\right] - \left(\dot{E}x_{ai} - \dot{E}x_{ao}\right) \quad (4.36)$$

Irreversibility calculation for the two expansion valves $\left(\dot{I}_{ExV}\right)$, solution pump $\left(\dot{I}_{SP}\right)$ and CTPs $\left(\dot{I}_{CTP}\right)$ are based on Guoy Stodola theorem i.e. $\dot{I} = T_o \dot{S}_{gen}$

4.4 Exergy analysis of the combined RRVPC and single effect H_2O–LiBr VARS

In the following subsections, the exergy based results of the combined reheat regenerative power cycle and the H_2O–LiBr VARS are presented and discussed along with first law based results presented in Chapter 3.

4.4.1 Effect of fuel mass flow rate on exergetic performance of the combined system

Effect of fuel flow rate variation on various performance parameters and irreversibility of system components is presented in Table 4.1. It is seen that the energy and exergy efficiencies of the power cycle vary very little with fuel flow rate and the exergy efficiency is lower than the energy efficiency at various fuel flow rates. Increase in fuel flow rate causes significant increase in the steam generation rate in the boiler and the net power. The EUF decreases because CL is fixed at 4000 TOR during fuel flow rate variation; both the net power and total fuel energy increase simultaneously, however the rate of increase of fuel energy is more compared to the net power. Exergetic efficiency of the CS is less than the EUF at all fuel flow rates and does not very much with it. Energy loss in the power cycle condenser also increases significantly with fuel flow rate. Irreversibility in various components of the power cycle including irreversibility of the exhaust gas and the CTPs shows an overall increase with fuel flow rate. On the other hand, irreversibility in the VARS components is not affected by variation in the fuel flow rate. VARS COP and exergetic efficiency is also independent of the fuel flow rate variation.

Due to increase in irreversibility of the topping cycle components it is seen that the total irreversibility of the overall system is more at higher fuel flow rate as shown in Fig. 4.1 No doubt the net power produced by the plant increases with fuel flow rate, but at the same time it also contributes significantly to energy loss in the power cycle condenser and the total system irreversibility. This is the reason that the energy and exergy efficiencies don't change much with the fuel flow rate.

Table 4.1: System performance and component irreversibility variation with fuel flow rate

		Fuel flow rate (kg/s)				
		5	10	15	20	25
Net power (MW)		43.813	88.823	133.113	176. 418	218.472
Steam generation rate (kg/s)		42.506	85.012	127.518	170.024	212.530
Efficiency of ST cycle (%)	Energy	35.323	35.805	35.772	35.557	35.227
	Exergy	33.306	33.761	33.730	33.528	33.216
EUF		0.466	0.414	0.395	0.384	0.375
COP	Actual	0.813	0.813	0.813	0.813	0.813
	Carnot	1.443	1.443	1.443	1.443	1.443
VARS exergetic efficiency (%)		11.817	11.817	11.817	11.817	11.817
Exergetic efficiency of CS (%)		32.814	33.507	33.560	33.401	33.116
Heat loss in power cycle condenser (kW)		47677.486	111687.948	175698.409	239708.871	303719.331
Irreversibility(kW)						
Boiler	$\dot{I}_{boiler}$	29287.783	58575.567	87863.350	117151.134	146438.917
Steam Turbine	$\dot{I}_{ST}$	5142.025	10802.652	16463.278	22123.905	27784.532
Power cycle condenser	$\dot{I}_{PCC}$	1957.202	4584.886	7212.571	9840.255	12467.940
Boiler feed pump	$\dot{I}_{BFP}$	54.901	109.709	164.517	219.325	274.133
Open water heater	$\dot{I}_{OWH}$	976.102	2111.209	3252.030	4392.850	5533.671
Closed water heater	$\dot{I}_{CWH}$	902.866	1805.731	2708.597	3611.462	4514.328
Mixing chamber 1	$\dot{I}_{MC1}$	1844.267	3815.316	5773.629	7730.863	9687.664
Mixing chamber 2	$\dot{I}_{MC2}$	0	0	0	0	0
Mixing chamber 3	$\dot{I}_{MC3}$	1102.203	1463.061	1659.212	1782.470	1867.101
Exhaust gas	$\dot{I}_{fg}$	44308.185	88616.371	132924.556	177232.742	221540.927
Cooling tower	$\dot{I}_{CT}$	3436.087	7326.132	11404.047	15585.261	19843.192
Cooling tower pumps	$\dot{I}_{CTP}$	1962.378	5295.171	11633.399	22103.872	37887.116
Generator	$\dot{I}_{G}$	4505.101	4505.101	4505.101	4505.101	4505.101
VARS condenser	$\dot{I}_{C}$	389.283	389.283	389.283	389.283	389.283
Expansion valve	$\dot{I}_{ExV}$	27.123	27.123	27.123	27.123	27.123
Evaporator	$\dot{I}_{E}$	377.225	377.225	377.225	377.225	377.225
Absorber	$\dot{I}_{A}$	806.339	806.339	806.339	806.339	806.339
Solution pump	$\dot{I}_{SP}$	0.108	0.108	0.108	0.108	0.108
Solution heat exchanger	$\dot{I}_{SHE}$	70.684	70.684	70.684	70.684	70.684
AC apparatus	$\dot{I}_{AC}$	1.992	1.992	1.992	1.992	1.992

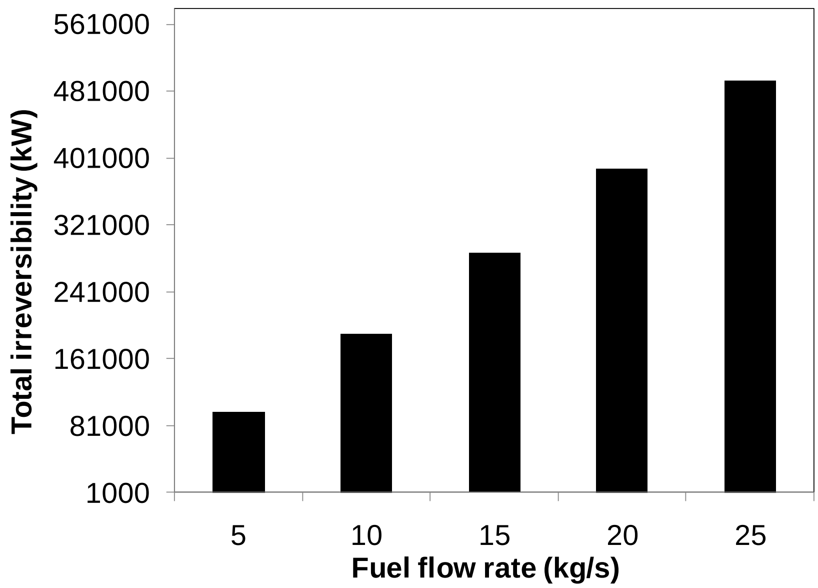

Fig.4.1: Total system irreversibility variation with fuel flow rate at P_b=150 bar, evaporator cooling capacity= 4000 TOR, T_G =80°C, T_C =35°C, T_E =10°C, T_A =35°C and SHE=75%.

4.4.2 Effect of boiler pressure on exergetic performance of the combined system

Effect of boiler pressure variation on performance and component irreversibility of the combined power and cooling system is presented in Table 4.2. It is seen that although the efficiencies of the power cycle don't change much with boiler pressure but the net power and efficiencies (energy and exergy) show their maximum values at boiler pressure of 150 bar. EUF variation with boiler pressure is similar with efficiencies because CL is kept fixed at 4000 TOR during boiler pressure variation too. Exergetic efficiency of the CS is also the maximum at 150 bar although it changes very little with boiler pressure. Losses in the power cycle condenser reduce initially with boiler pressure; minimum losses occur at 150 bar and further increase in pressure results in increase of losses. The boiler irreversibility reduces with increase in boiler pressure while the irreversibility in the ST, MC1 increases. Irreversibility in the power cycle condenser, MC3, the CT and the CTPs are minimum at 150 bar. Exhaust irreversibility remain unchanged with boiler pressure variation. OWH irreversibility increases with boiler pressure up to 175 bar and then again decreases at 200 bar. BFP and CWH irreversibility doesn't follow any specific trend.

Further, it was found that MC2 irreversibility is zero at all boiler pressures except at 100 bar. The entropy at points 14, 16 and 17 with boiler pressure change in such a way that only at 100 bar boiler pressure the entropy generated is 0.000953 kJ/kgK. At other boiler pressures, the entropy generation was found to be zero. In the VARS, boiler pressure variation has no effect on irreversibility of the components other than in the generator where irreversibility decreases with increase in boiler pressure; becomes minimum at 150 bar and remain constant thereafter. The total irreversibility of the overall system, as can be seen from Fig. 4.2 is the minimum at 150 bar.

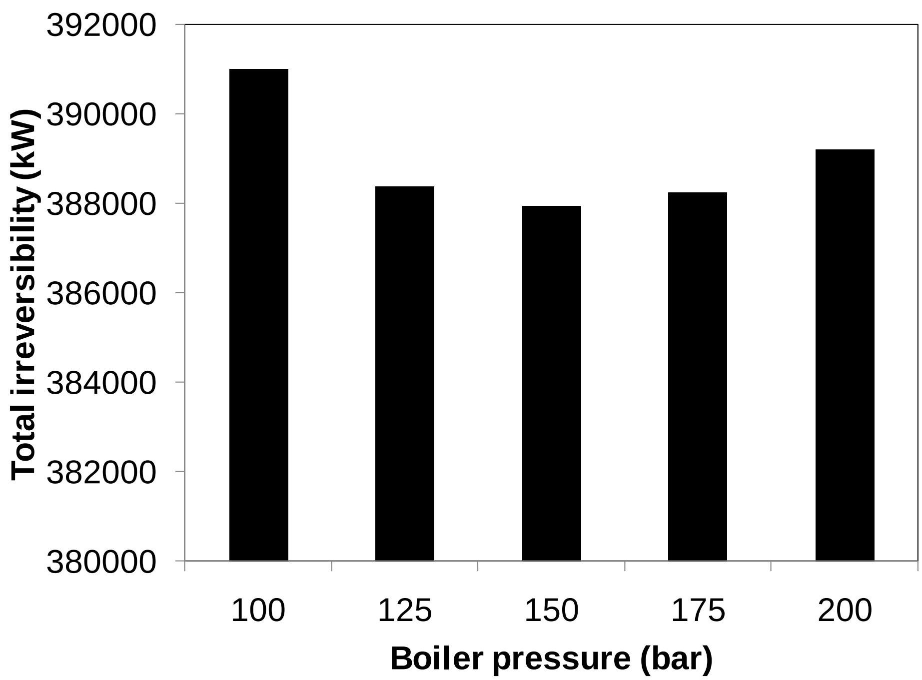

Fig.4.2: Total system irreversibility variation with boiler pressure at $\dot{m}_f$ = 20 kg/s, evaporator cooling capacity= 4000 TOR, T_G =80°C, T_C =35°C, T_E =10°C, T_A =35°C and SHE=75%.

Table 4.2: System performance and component irreversibility variation with boiler pressure

		Boiler pressure (bar)				
		100	125	150	175	200
Net power (MW)		173.433	175.852	176.418	176.393	175.795
Steam generation (kg/s)		166.380	168.193	170.024	171.979	174.080
Efficiency of ST cycle (%)	Energy	34.956	35.443	35.557	35.552	35.432
	Exergy	32.960	33.420	33.528	33.523	33.409
EUF		0.378	0.383	0.384	0.384	0.383
Heat loss in power cycle condenser (kW)		242592.962	240268.424	239708.871	239716.576	240268.299
COP	Actual	0.813	0.813	0.813	0.813	0.813
	Carnot	1.443	1.443	1.443	1.443	1.443
VARS exergetic efficiency (%)		11.817	11.817	11.817	11.817	11.817
Exergetic efficiency of CS (%)		32.832	33.290	33.401	33.396	33.284
Irreversibility(kW)						
Boiler	$\dot{I}_{boiler}$	124242.705	120213.538	117151.134	114700.387	112709.891
Steam Turbine	$\dot{I}_{ST}$	19339.267	20253.421	22123.905	24254.521	26484.709
Power cycle condenser	$\dot{I}_{PCC}$	9958.650	9863.225	9840.255	9840.572	9863.220
Boiler Feed pump	$\dot{I}_{BFP}$	170.904	139.035	219.325	660.745	336.026
Open water heater	$\dot{I}_{OWH}$	3641.912	4065.003	4392.850	4401.688	4357.741
Closed water heater	$\dot{I}_{CWH}$	2622.010	3260.291	3611.462	3504.648	4165.137
Mixing chamber 1	$\dot{I}_{MC1}$	7230.676	7485.482	7730.863	7998.888	8272.575
Mixing chamber 2	$\dot{I}_{MC2}$	47.263	0	0	0	0
Mixing chamber 3	$\dot{I}_{MC3}$	1786.954	1783.346	1782.470	1782.482	1783.345
Exhaust gas	$\dot{I}_{fg}$	177232.741	177232.742	177232.742	177232.742	177232.742
Cooling tower	$\dot{I}_{CT}$	15775.562	15622.170	15585.261	15585.769	15622.162
Cooling tower pumps	$\dot{I}_{CTP}$	22691.681	22217.069	22103.872	22105.427	22217.043
Generator	$\dot{I}_{G}$	4593.514	4575.698	4505.101	4505.101	4505.101
VARS condenser	$\dot{I}_{C}$	389.282	389.282	389.282	389.282	389.282
Expansion valve	$\dot{I}_{ExV}$	27.123	27.123	27.123	27.123	27.123
Evaporator	$\dot{I}_{E}$	377.225	377.225	377.225	377.225	377.225
Absorber	$\dot{I}_{A}$	806.339	806.339	806.339	806.339	806.339
Solution pump	$\dot{I}_{SP}$	0.108	0.108	0.108	0.108	0.108
Solution heat exhanger	$\dot{I}_{SHE}$	70.684	70.684	70.684	70.684	70.684
AC apparatus	$\dot{I}_{AC}$	1.992	1.992	1.992	1.992	1.992

4.4.3Effect of evaporator cooling capacity on exergetic performance of the combined system

Plant performance and irreversibility in various system components as function of evaporator cooling capacity is shown in Table 4.3. Like the energy efficiency, the power cycle exergy efficiency also reduces very little with evaporator cooling capacity and it is lower than the energy efficiency. Although the net power reduces slightly with cooling capacity, the EUF however shows marginal gain because of increase in the amount of cooling produced. CS exergetic efficiency however reduces slightly with increase in cooling capacity.

The energy loss in the power cycle condenser reduces with increase in cooling capacity due to flow of lesser amount of steam through it. Amount of steam extracted and required for vapor generation in the generator is more at higher cooling capacity; hence the steam flow rate through the power cycle condenser decreases.

The same is also the reason for lower irreversibility in the power cycle condenser. Irreversibility in the boiler, CWH, BFP and the exhaust irreversibility are not affected due to cooling capacity variation. However ST, OWH, CT and MC1 irreversibility decreases with increase in cooling capacity. Contrary to this, irreversibility in the MC3 and the CTPs are more at higher cooling capacity. Increase in cooling capacity however affects working of the VARS more, as we can see from Table 4.3 that the irreversibility in all the VARS components increases with cooling capacity and hence the total irreversibility also becomes more at higher cooling capacity (Fig. 4.3).

Table 4.3: System performance and component irreversibility variation with evaporator cooling capacity

		TOR				
		2000	2500	3000	3500	4000
Net power (MW)		178.614	178.110	177.577	177.014	176.418
Steam generation rate (kg/s)		170.024	170.024	170.024	170.024	170.024
Efficiency of ST cycle (%)	Energy	35.999	35.898	35.791	35.677	35.557
	Exergy	33.945	33.849	33.748	33.641	33.528
EUF		0.374	0.377	0.379	0.381	0.384
COP	Actual	0.813	0.813	0.813	0.813	0.813
	Carnot	1.443	1.443	1.443	1.443	1.443
VARS exergetic efficiency (%)		11.817	11.817	11.817	11.817	11.817
Exergetic efficiency of CS (%)		33.880	33.769	33.652	33.530	33.401
Heat loss in power cycle condenser (kW)		247875.358	245833.736	243792.114	241750.492	239708.871
Irreversibility (kW)						
Boiler	$\dot{I}_{boiler}$	117151.134	117151.134	117151.134	117151.134	117151.134
Steam Turbine	$\dot{I}_{ST}$	22383.206	22318.381	22253.556	22188.730	22123.905
Condenser	$\dot{I}_{PCC}$	10175.496	10091.686	10007.876	9924.066	9840.255
Boiler feed pump	$\dot{I}_{BFP}$	219.277	219.290	219.301	219.313	219.325
Open water heater	$\dot{I}_{OWH}$	4478.066	4456.763	4435.459	4414.154	4392.850
Closed water heater	$\dot{I}_{CWH}$	3611.462	3611.462	3611.462	3611.462	3611.462
Mixing chamber 1	$\dot{I}_{MC1}$	7778.544	7766.777	7754.907	7742.936	7730.863
Mixing chamber 2	$\dot{I}_{MC2}$	0	0	0	0	0
Mixing chamber 3	$\dot{I}_{MC3}$	1000.599	1213.883	1414.475	1603.638	1782.470
Exhaust gas	$\dot{I}_{fg}$	177232.742	177232.742	177232.742	177232.742	177232.742
Cooling tower	$\dot{I}_{CT}$	16164.111	16000.494	15850.281	15712.230	15585.261
Cooling tower pumps	$\dot{I}_{CTP}$	17120.790	18145.677	19335.934	20660.367	22103.872
Generator	$\dot{I}_{G}$	2252.551	2815.688	3378.826	3941.963	4505.101
VARS condenser	$\dot{I}_{C}$	194.641	243.302	291.962	340.622	389.282
Expansion valve	$\dot{I}_{ExV}$	13.561	16.952	20.342	23.733	27.123
Evaporator	$\dot{I}_{E}$	188.612	235.766	282.919	330.072	377.225
Absorber	$\dot{I}_{A}$	403.169	503.962	604.754	705.546	806.339
Solution pump	$\dot{I}_{SP}$	0.054	0.068	0.081	0.095	0.108
Solution heat exchanger	$\dot{I}_{SHE}$	35.342	41.177	53.013	61.848	70.684
AC apparatus	$\dot{I}_{AC}$	1.939	1.958	1.971	1.982	1.992

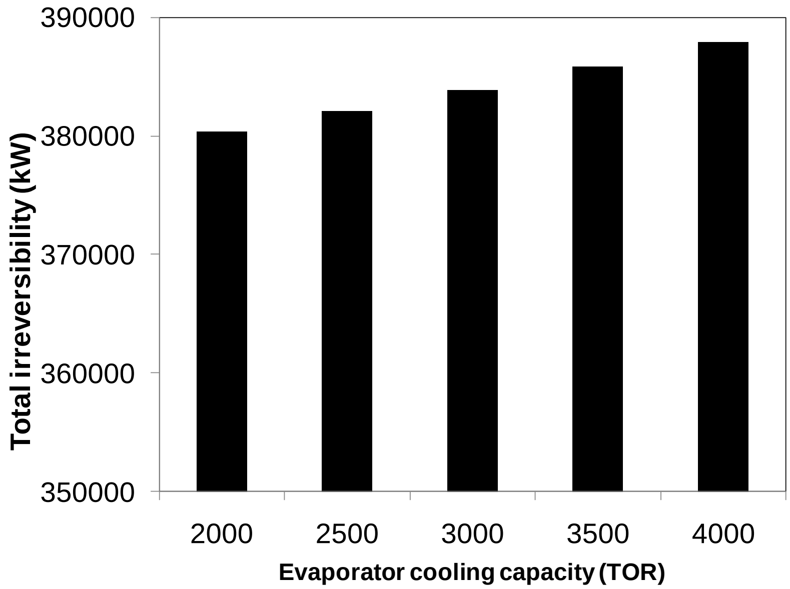

Fig.4.3: Total system irreversibility variation with evaporator cooling capacity at P_b=150 bar, $\dot{m}_f$ = 20 kg/s, T_G =80°C, T_C =35°C, T_E =10°C, T_A =35°C and SHE=75%.

4.4.4 Effect of VARS generator temperature on exergetic performance of the combined system

Table 4.4 shows plant performance and component irreversibility variation with VARS generator temperature (T_G) for fixed absorber temperature (T_A) and VARS condenser temperature (T_C) of 35°C; evaporator temperature (T_E) of 10°C and SHE efficiency of 75%. Net power and efficiencies of the power cycle, EUF of the combined cycle and COP of the VARS show its maximum values at T_G =80°C. Power cycle condenser loss is the minimum at T_G =80°C, and all the efficiencies are showing their maximum values at this T_G because maximum power is obtained at T_G =80°C with minimum steam extraction rate from the ST. Maximum COP is also obtained at this generator temperature, detail explanation about all these variations was highlighted in Chapter 3. VARS exergetic efficiency shows a gradual decrease with T_G. Boiler, exhaust and CWH irreversibility do not change at all with T_G.

Irreversibility in the ST, MC3, CT and CTPs changes with T_G in such a way that these are minimum at T_G =80°C. OWH irreversibility decreases with T_G. Irreversibility in MC1 and BFPs decreases with T_G but these are the lowest at 90°C. In the VARS however, irreversibility in the generator, condenser and absorber increases while the solution pump decreases with increase in T_G. SHE irreversibility is the minimum at T_G =80°C. Irreversibility in the evaporator, AC apparatus and the expansion valve remain unchanged with T_G. These variations finally give a minimum value of total system irreversibility at T_G =80°C as shown in Fig. 4.4.

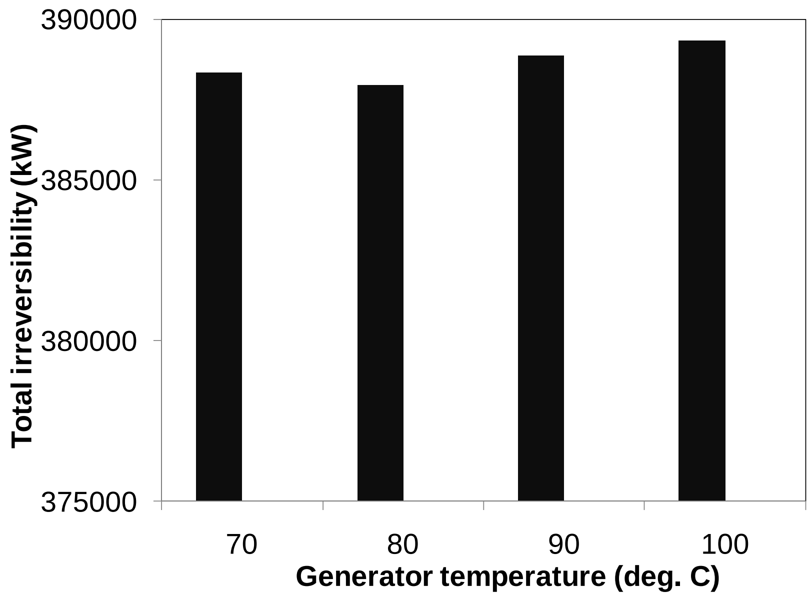

Fig.4.4: Total system irreversibility variation with T_G at P_b=150 bar, $\dot{m}_f$ = 20 kg/s, evaporator cooling capacity= 4000 TOR, T_C =35°C, T_E =10°C, T_A =35°C and SHE=75%.

Table 4.4: System performance and component irreversibility variation with VARS generator temperature

		Generator temperature (°C)			
		70	80	90	100
Net power (MW)		175.970	176.418	175.980	175.943
Steam generation rate (kg/s)		170.024	170.024	170.024	170.024
Efficiency of ST cycle (%)	Energy	35.467	35.557	35.469	35.462
	Exergy	33.442	33.528	33.444	33.437
EUF		0.383	0.384	0.383	0.383
COP	Actual	0.799	0.813	0.801	0.789
	Carnot	1.155	1.443	1.715	1.973
VARS exergetic efficiency (%)		13.346	11.817	11.351	11.127
Exergetic efficiency of CS (%)		33.339	33.401	33.341	33.332
Heat loss in power cycle condenser (kW)		239931.555	239708.871	239986.351	239727.677
Irreversibility (kW)					
Boiler	$\dot{I}_{boiler}$	117151.134	117151.134	117151.134	117151.134
Steam Turbine	$\dot{I}_{ST}$	22752.691	22123.905	22754.406	22746.313
Condenser	$\dot{I}_{PCC}$	9849.397	9840.255	9851.646	9841.027
Boiler feed pump	$\dot{I}_{BFP}$	333.877	219.325	333.503	335.269
Open water heater	$\dot{I}_{OWH}$	4429.484	4392.850	4429.920	4427.859
Closed water heater	$\dot{I}_{CWH}$	3611.462	3611.462	3611.462	3611.462
Mixing chamber 1	$\dot{I}_{MC1}$	7737.712	7730.863	7738.002	7736.633
Mixing chamber 2	$\dot{I}_{MC2}$	0	0	0	0
Mixing chamber 3	$\dot{I}_{MC3}$	1786.309	1782.470	1785.723	1788.469
Exhaust gas	$\dot{I}_{fg}$	177232.742	177232.742	177232.742	177232.742
Cooling tower	$\dot{I}_{CT}$	15612.784	15585.261	15613.920	15608.526
Cooling tower pumps	$\dot{I}_{CTP}$	22275.617	22103.872	22278.571	22358.775
Generator	$\dot{I}_{G}$	4118.696	4505.101	4167.451	4372.278
VARS condenser	$\dot{I}_{C}$	374.162	389.282	407.086	427.441
Expansion valve	$\dot{I}_{ExV}$	27.123	27.123	27.123	27.123
Evaporator	$\dot{I}_{E}$	377.225	377.225	377.225	377.225
Absorber	$\dot{I}_{A}$	590.798	806.339	1023.192	1237.610
Solution pump	$\dot{I}_{SP}$	0.244	0.108	0.075	0.061
Solution heat exchanger	$\dot{I}_{SHE}$	86.253	70.684	81.912	72.632
AC apparatus	$\dot{I}_{AC}$	1.992	1.992	1.992	1.992

4.4.5 Effect of VARS condenser temperature on exergetic performance of the combined system

Plant performance and component irreversibility variation with condenser temperature (T_C) is represented in Table 4.5. Net power, efficiencies of the power cycle and EUF of the combined plant are not much sensitive to T_C variation, decreases very little with T_C although the energy loss in the power cycle condenser (PCC) decreases from 239708.87 kW to 238064.516 kW during T_C increase from 35°C to 45°C. COP decreases with increase in T_C and thus it is the maximum at 35°C. VARS and CS exergetic efficiency also decreases little with T_C. Change in T_C has no effect on boiler, exhaust and CWH irreversibility. Irreversibility in ST, power cycle condenser, MC1, CT and OWH decreases with increase in T_C while the irreversibility in the MC3 and CTPs shows an increasing trend. BFP irreversibility doesn't change much with T_C.

In the VARS, irreversibility in the generator and the absorber decreases while in the condenser, solution pump, SHE and the expansion valves; irreversibility increases with increase in T_C. In the evaporator and AC apparatus however irreversibility doesn't change with T_C. As can be seen from Fig. 4.5, the total irreversibility of the combined system does not change much with T_C; the minimum total irreversibility was observed at 37.5°C.

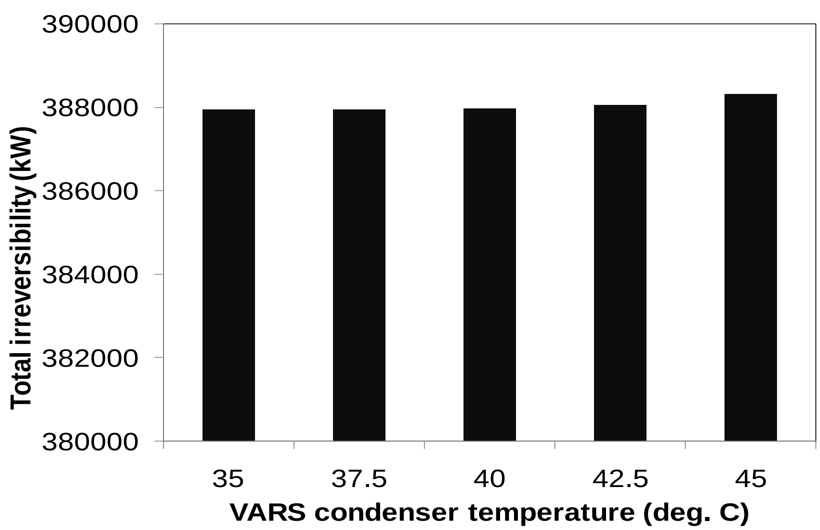

Fig. 4.5: Total system irreversibility variation with T_C at P_b=150 bar, $\dot{m}_f$ = 20 kg/s, evaporator cooling capacity= 4000 TOR, T_G =80°C, T_E =10°C, T_A =35°C and SHE=75%.

Table 4.5: System performance and component irreversibility variation with VARS condenser temperature

		Condenser temperature (°C)				
		35	37.5	40	42.5	45
Net power(MW)		176.418	176.396	176.358	176.291	176.143
Steam generation rate(kg/s)		170.024	170.024	170.024	170.024	170.024
Efficiency of ST cycle (%)	Energy	35.557	35.553	35.545	35.532	35.502
	Exergy	33.528	33.523	33.516	33.504	33.475
EUF		0.384	0.384	0.384	0.383	0.383
COP	Actual	0.813	0.806	0.795	0.776	0.738
	Carnot	1.443	1.312	1.203	1.110	1.031
VARS exergetic efficiency (%)		11.817	11.719	11.563	11.289	10.734
Exergetic efficiency of CS (%)		33.401	33.395	33.386	33.368	33.330
Heat loss in power cycle condenser(kW)		239708.871	239573.349	239350.851	238946.585	238064.516
Irreversibility (kW)						
Boiler	$\dot{I}_{boiler}$	117151.134	117151.134	117151.134	117151.134	117151.134
Steam Turbine	$\dot{I}_{ST}$	22123.905	22119.602	22112.537	22099.701	22071.694
Condenser	$\dot{I}_{PCC}$	9840.255	9834.692	9825.558	9808.963	9772.753
Boiler feed pump	$\dot{I}_{BFP}$	219.325	219.326	219.327	219.329	219.334
Open water heater	$\dot{I}_{OWH}$	4392.850	4391.436	4389.115	4384.896	4375.692
Closed water heater	$\dot{I}_{CWH}$	3611.462	3611.462	3611.462	3611.462	3611.462
Mixing chamber 1	$\dot{I}_{MC1}$	7730.863	7730.058	7728.735	7726.329	7721.065
Mixing chamber 2	$\dot{I}_{MC2}$	0	0	0	0	0
Mixing chamber 3	$\dot{I}_{MC3}$	1782.470	1783.935	1786.328	1790.635	1799.853
Exhaust gas	$\dot{I}_{fg}$	177232.742	177232.742	177232.742	177232.742	177232.742
Cooling tower	$\dot{I}_{CT}$	15585.261	15582.491	15577.957	15569.763	15552.079
Cooling tower pumps	$\dot{I}_{CTP}$	22103.872	22141.744	22204.013	22317.708	22568.749
Generator	$\dot{I}_{G}$	4505.101	4405.982	4315.841	4239.384	4194.171
VARS condenser	$\dot{I}_{C}$	389.282	500.745	610.649	719.027	825.914
Expansion valve	$\dot{I}_{ExV}$	27.123	32.780	38.967	45.686	52.935
Evaporator	$\dot{I}_{E}$	377.225	377.225	377.225	377.225	377.225
Absorber	$\dot{I}_{A}$	806.339	747.634	691.309	641.776	612.588
Solution pump	$\dot{I}_{SP}$	0.108	0.152	0.219	0.339	0.592
Solution heat exchanger	$\dot{I}_{SHE}$	70.684	79.721	94.958	123.455	187.193
AC apparatus	$\dot{I}_{AC}$	1.992	1.992	1.992	1.992	1.992

4.4.6 Effect of VARS evaporator temperature on exergetic performance of the combined system

Increase in evaporator temperature $\left(T_E\right)$ causes slight improvement in the performance of the combined power and cooling system (refer Table 4.6). This improvement in performance takes place in–spite of some increase in the condenser energy loss; probably due to increase in the net power output caused by reduction in the steam extraction rate required for VARS generator at higher evaporator temperature. Irreversibility results due to T_E variation shows that the increase in T_E doesn't affect the boiler, exhaust and CWH irreversibility. Irreversibility in ST, power cycle condenser, OWH, CT and MC1 increases with increase in T_E while in the MC3 and CTPs, it shows a decreasing trend. Irreversibility in the BFPs decreases but very little, the effect is almost negligible. In the VARS components, irreversibility reduces with increase in T_E except in the absorber where it shows an opposite trend.

Irreversibility in the AC apparatus is not changed due to increase in T_E . The percentage decrease in irreversibility of the generator, condenser, expansion valve, evaporator and SHE are 3.60%, 0.77%, 57.90%, 81.09% and 63.41% respectively due to T_E increase from 5°C to 15°C. As a result, the total system irreversibility decreases with increase in T_E (Fig. 4.6).

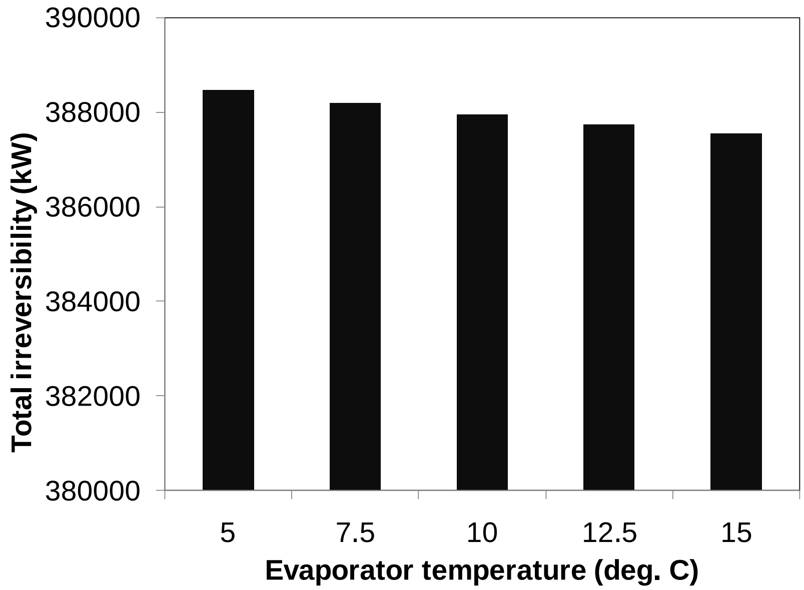

Fig. 4.6: Total system irreversibility variation with T_E at P_b=150 bar, $\dot{m}_f$ = 20 kg/s, evaporator cooling capacity= 4000 TOR, T_G =80°C, T_C =35°C, T_A =35°C and SHE=75%.

Table 4.6: System performance and component irreversibility variation with VARS evaporator temperature

		Evaporator temperature (°C)				
		5	7.5	10	12.5	15
Net power(MW)		176.272	176.356	176.418	176.468	176.510
Steam generation rate(kg/s)		170.024	170.024	170.024	170.024	170.024
Efficiency of ST cycle (%)	Energy	35.528	35.545	35.557	35.567	35.576
	Exergy	33.500	33.516	33.528	33.537	33.545
EUF		0.383	0.384	0.384	0.384	0.384
COP	Actual	0.771	0.795	0.813	0.828	0.841
	Carnot	1.181	1.300	1.443	1.618	1.836
VARS exergetic efficiency (%)		11.215	11.553	11.817	12.039	12.235
Exergetic efficiency of CS (%)		33.363	33.385	33.401	33.414	33.425
Heat loss in the power cycle condenser (kW)		238832.214	239336.630	239708.871	240010.118	240266.245
Irreversibility(kW)						
Boiler	$\dot{I}_{boiler}$	117151.134	117151.134	117151.134	117151.134	117151.134
Steam Turbine	$\dot{I}_{ST}$	22096.070	22112.086	22123.905	22133.470	22141.603
Condenser	$\dot{I}_{PCC}$	9804.268	9824.974	9840.255	9852.622	9863.136
Boiler feed pump	$\dot{I}_{BFP}$	219.330	219.327	219.325	219.323	219.322
Open water heater	$\dot{I}_{OWH}$	4383.703	4388.966	4392.850	4395.994	4398.666
Closed water heater	$\dot{I}_{CWH}$	3611.462	3611.462	3611.462	3611.462	3611.462
Mixing chamber 1	$\dot{I}_{MC1}$	7725.648	7728.651	7730.863	7732.651	7734.169
Mixing chamber 2	$\dot{I}_{MC2}$	0	0	0	0	0
Mixing chamber 3	$\dot{I}_{MC3}$	1791.842	1786.479	1782.470	1779.192	1776.383
Exhaust gas	$\dot{I}_{fg}$	177232.742	177232.742	177232.742	177232.742	177232.742
Cooling tower	$\dot{I}_{CT}$	15567.446	15577.663	15585.261	15591.445	15596.728
Cooling tower pumps	$\dot{I}_{CTP}$	22353.832	22209.826	22103.872	22018.263	21945.541
Generator	$\dot{I}_{G}$	4598.718	4547.394	4505.101	4467.598	4433.125
VARS condenser	$\dot{I}_{C}$	390.791	390.035	389.282	388.534	387.789
Expansion valve	$\dot{I}_{ExV}$	40.145	33.270	27.123	21.675	16.899
Evaporator	$\dot{I}_{E}$	642.219	508.541	377.225	248.209	121.432
Absorber	$\dot{I}_{A}$	743.682	773.560	806.339	840.269	875.217
Solution pump	$\dot{I}_{SP}$	0.186	0.138	0.108	0.088	0.072
Solution heat exchanger	$\dot{I}_{SHE}$	121.486	91.093	70.684	55.782	44.455
AC apparatus	$\dot{I}_{AC}$	1.992	1.992	1.992	1.992	1.992

4.4.7 Effect of VARS absorber temperature on exergetic performance of the combined system

Effect of absorber temperature (T_A) variation on performance and irreversibility of system components is shown in Table 4.7. As can be seen, the performance of the topping power cycle is not affected much by increase in T_A; only a slight reduction is noticed. With increase in T_A, amount of extracted steam from ST to the generator and CT side pumping power increases and this affects the power and efficiencies as discussed in chapter 3. The EUF and exergetic efficiency of the combined plant also reduce slightly with T_A. Losses in the power cycle condenser however reduce with T_A. The COP and exergetic efficiency of the VARS both reduces by 8% when T_A is increased from 35°C to 45°C. Irreversibility in the boiler, flue gas exhaust and the CWH does not change with increase in T_A. Irreversibility in the ST, power cycle condenser, OWH, CT and MC1 however decreases while it increases for the MC3 and CTPs. Irreversibility in the BFPs increases but very little almost negligible.

In the VARS components, there is no effect of change of T_A on irreversibility of the condenser, evaporator, AC apparatus and the expansion valves. The generator, absorber and the SHE irreversibility increases to 2.50%, 50.61% and 82.69% respectively while the irreversibility in the solution pump increases to values more than double of its original values during T_A increase from 35°C to 45°C. Fig. 4.7 shows that the total irreversibility of the combined system increases with T_A.

Table 4.7: System performance and component irreversibility variation with VARS absorber temperature

		Absorber temperature (°C)				
		35	37.5	40	42.5	45
Net power(MW)		176.418	176.386	176.344	176.285	176.182
Steam generation rate(kg/s)		170.024	170.024	170.024	170.024	170.024
Efficiency of ST cycle (%)	Energy	35.557	35.551	35.543	35.530	35.509
	Exergy	33.528	33.522	33.514	33.502	33.483
EUF		0.384	0.384	0.384	0.384	0.383
COP	Actual	0.813	0.803	0.791	0.775	0.748
	Maximum	1.443	1.363	1.283	1.203	1.122
VARS exergetic efficiency (%)		11.817	11.678	11.505	11.265	10.873
Exergetic efficiency of CS (%)		33.401	33.393	33.382	33.367	33.339
Heat loss in the power cycle condenser (kW)		239708.871	239515.060	239266.150	238910.102	238292.981
Irreversibility (kW)						
Boiler	$\dot{I}_{boiler}$	117151.134	117151.134	117151.134	117151.134	117151.134
Steam Turbine	$\dot{I}_{ST}$	22123.905	22117.751	22109.848	22098.543	22078.948
Condenser	$\dot{I}_{PCC}$	9840.255	9832.299	9822.081	9807.465	9782.131
Boiler feed pump	$\dot{I}_{BFP}$	219.325	219.326	219.327	219.329	219.333
Open water heater	$\dot{I}_{OWH}$	4392.850	4390.828	4388.231	4384.515	4378.076
Closed water heater	$\dot{I}_{CWH}$	3611.462	3611.462	3611.462	3611.462	3611.462
Mixing chamber 1	$\dot{I}_{MC1}$	7730.863	7729.712	7728.232	7726.111	7722.431
Mixing chamber 2	$\dot{I}_{MC2}$	0	0	0	0	0
Mixing chamber 3	$\dot{I}_{MC3}$	1782.470	1784.563	1787.234	1791.020	1797.486
Exhaust gas	$\dot{I}_{fg}$	177232.742	177232.742	177232.742	177232.741	177232.741
Cooling tower	$\dot{I}_{CT}$	15585.261	15581.299	15576.231	15569.019	15556.623
Cooling tower pumps	$\dot{I}_{CTP}$	22103.872	22157.743	22227.257	22327.319	22502.464
Generator	$\dot{I}_{G}$	4505.101	4523.442	4545.328	4573.936	4617.891
VARS condenser	$\dot{I}_{C}$	389.282	389.282	389.282	389.282	389.282
Expansion valve	$\dot{I}_{ExV}$	27.123	27.123	27.123	27.123	27.123
Evaporator	$\dot{I}_{E}$	377.225	377.225	377.225	377.225	377.225
Absorber	$\dot{I}_{A}$	806.339	897.116	991.331	1092.901	1214.468
Solution pump	$\dot{I}_{SP}$	0.108	0.128	0.157	0.205	0.298
Solution heat exchanger	$\dot{I}_{SHE}$	70.684	78.379	88.376	102.966	129.137
AC apparatus	$\dot{I}_{AC}$	1.992	1.992	1.992	1.992	1.992

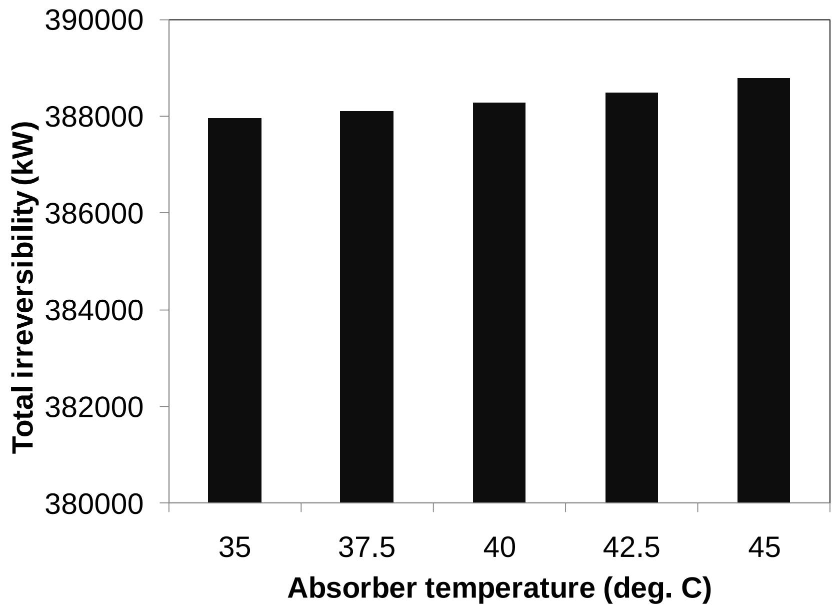

Fig. 4.7: Total system irreversibility variation with T_A at P_b=150 bar, $\dot{m}_f$ = 20 kg/s, evaporator cooling capacity= 4000 TOR, T_G =80°C, T_C =35°C, T_E =10°C and SHE=75%.

4.4.8 Irreversibility distribution among various system components

Contribution of each system component to total irreversibility is separately shown for the topping cycle and major VARS components in Fig. 4.8(a) and 4.8(b). Exergy loss accompanying the exhaust flue gas at 300°C is found to be the maximum (45.63%). The next major contributor to total irreversibility is the boiler with a contribution of 30.16%, thus a crucial component of the topping RRVPC. Irreversibility contribution of the ST, CT, CTPs, MC1, MC3, power cycle condenser, OWH and CWH are 22.124 MW, 15.585 MW, 22.104 MW, 7.731 MW, 1.782 MW, 9.840 MW, 4.393 MW and 3.611 MW against a total irreversibility of 387.952 MW. In the VARS as shown in Fig. 4.8 (b), irreversibility is the highest in the generator. The absorber, condenser, evaporator and SHE, are the next major contributors. The irreversibility values in these devices are 4.505 MW, 0.806 MW, 0.389 MW 0.377 MW and 70.684 kW respectively. In the work of Khaliq [7], with T_G =80°C, T_A and T_C both maintained at 35°C and T_E at 10°C, the order in which the VARS components appear in terms of maximum exergy destruction are the generator, absorber, condenser, evaporator and the SHE respectively. Similar trend is observed in the present work too.

However, the exergy destruction in the respective components is of higher magnitudes compared to that of [7]. The source of heat for the VARS generator in [7] was the stack gas off the heat recovery steam generator and the refrigerant mass flow rate was determined from energy balance in the generator. In the present case, the irreversibility values shown in Fig. 4.8 (b) correspond to a cooling capacity of 4000 TOR (14000 kW). In Ref. [7], the refrigerant flow rate and the amount of cold produced were not mentioned specifically. In the present study, the flow rate of refrigerant, weak and strong solution are 5.901 kg/s, 36.007 kg/s and 41.908 kg/s respectively [as reported in chapter 3]. May be these changes in the flow rates are responsible for comparatively higher exergy destruction in the VARS components. Water side inlet and outlet temperatures in the VARS condenser, evaporator and absorber are same with that of [7]. The BFPs and MC2 of the power cycle and expansion valves, solution pump and the AC apparatus contribute very little and their effects on total irreversibility are negligible and not shown in the figures.

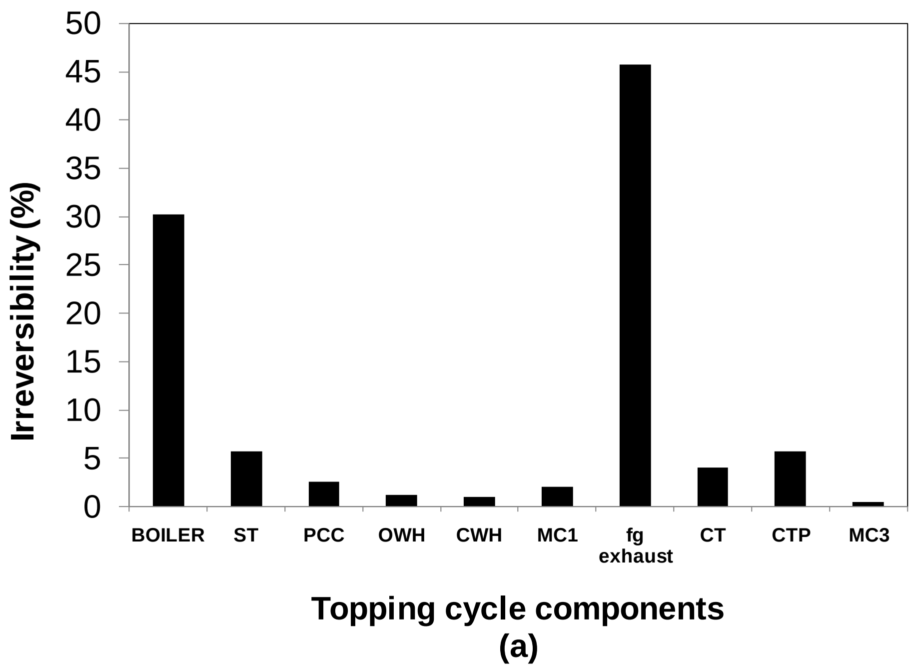

Fig. 4.8(a): Irreversibility distribution among the topping cycle components at P_b=150 bar, $\dot{m}_f$ = 20 kg/s, evaporator cooling capacity= 4000 TOR, T_G =80°C, T_C =35°C, T_E =10°C, T_A =35°C and SHE=75%.

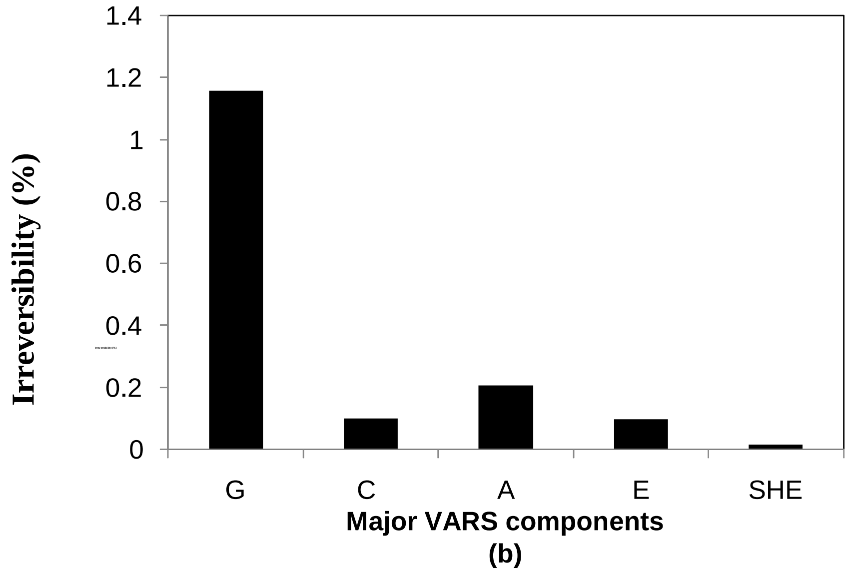

Fig. 4.8 (b): Irreversibility distribution among the major VARS components at P_b=150 bar, $\dot{m}_f$ = 20 kg/s, evaporator cooling capacity= 4000 TOR, T_G =80°C, T_C =35°C, T_E =10°C, T_A =35°C and SHE=75%

4.5 Summary

The exergetic performance of a combined reheat regenerative vapor power cycle and LiBr based VARS has been simulated in this chapter as extension of the previous work described in Chapter 3. A detail second law based parametric study is carried out to identify the importance of various operating parameters such as boiler pressure, fuel flow rate, evaporator cooling capacity and operating temperature of VARS components on exergy efficiency of the power cycle, VARS exergetic efficiency and more importantly the irreversible losses in various components of the combined power and cooling system. The parametric exergy analysis based on variation of the above parameters yields a detailed insight on the influence of these variables on the component and total irreversibility of the combined system. The details regarding variation of net power and efficiency of the power cycle and variation of VARS COP and thermal loads in VARS components with the above mentioned operating parameters were presented in Chapter 3. Increase in fuel flow rate to the boiler furnace directly affect the net power production of the power plant which increases from 43.813 MW at 5 kg s^{-1} to 218.472 MW at 25 kg s^{-1}, however at the same time it also leads to increase in irreversible losses in all the power cycle components including the irreversibility accompanying the flue gas exhaust. EUF of the combined plant however decreases with increase in fuel flow rate. The effect of variation of fuel flow rate and boiler pressure on energy and exergy efficiencies of the power cycle is almost negligible. Moreover, the energetic and exergetic performance of the VARS and its components' irreversibility are not affected due to variation of these two parameters except in the generator where we see that the irreversibility decreases with increase in boiler pressure and it is the lowest at 150 bar and remain constant thereafter after up to 200 bar. The exergy efficiency of the power plant is lower than its corresponding energy efficiency. It was reported in Chapter 3 that the net power and first law based efficiency of the power cycle was the maximum at 150 bar boiler pressure. In the present study also we observe that the power cycle exergy efficiency, EUF and exergetic efficiency of the CS show their maximum value at this boiler pressure. The total irreversibility of the system components is also the lowest at 150 bar boiler pressure.

With increase in evaporator cooling capacity from 2000 to 4000 TOR, the net power produced by the power plant reduces by 1.229%; the efficiencies (energy and exergy) also reduce slightly. Exergetic efficiency of the CS also reduces slightly with increase in evaporator cooling capacity. Due to more steam extraction from the ST to the VARS generator at higher cooling capacity, the ST power reduces; it also affects the irreversibility in the ST and some of the downstream components viz. the power cycle condenser, CT, OWH and MC1 where the irreversible losses decrease with increase in cooling capacity while in the MC3 and the CTPs and also in all the VARS components the irreversibility increases. Overall effect is that the total system irreversibility is more at higher cooling capacity. Irreversibility in the boiler, CWH, exhaust and the BFPs, VARS COP and its exergetic efficiency are not affected by cooling capacity variation.

In Chapter 3 it was shown that that the net power, energy efficiency of the topping power cycle and COP of the bottoming VARS was the highest at T_G =80°C with other VARS component temperatures fixed at T_C =35°C, T_E =10°C, T_A=35°C and SHE efficiency of 75%. From the present exergy analysis too it is found that the exergetic efficiency of both the power only cycle and the CS are maximum at T_G =80 $^{\circ}$C. The irreversibility in the CS components (excluding the boiler, CWH and the flue gas exhaust irreversibility) changes in such a way that the total system irreversibility is finally the lowest at T_G =80°C. VARS exergetic efficiency however shows a gradual decrease with T_G .

The performance parameters of the power cycle (net power, energy and exergy efficiencies), the VARS (COP and exergetic efficiency) and the EUF, exergetic efficiency of the combined cycle; although not much sensitive to T_C variation but all these parameters reduce with increase in T_C . Irreversibility in some components of the topping and bottoming cycle reduces while it increases in some other components, but overall the total system irreversibility increases with T_C . The total minimum irreversibility is however observed at T_C =37.5°C with a little difference with irreversibility at T_C =35 $^{\circ}$C.

Increase in T_E cause slight improvement in performance of both the power cycle and the cooling system. Except in the ST, power cycle condenser, CT, OWH and MC1; irreversibility in all other components of the power cycle and most of the VARS components (except the absorber) reduces, hence the total system irreversibility is less at higher T_E . The irreversibility in boiler, CWH and flue gas exhaust of the topping and A/C apparatus of the cooling cycle is not affected by T_E variation.

Energetic and exergetic performance of the power cycle, VARS and the CS reduces with increase in absorber temperature T_A. Irreversibility in the boiler, CWH and the flue gas exhaust of the power cycle and condenser, evaporator, AC apparatus and the expansion valves of the VARS remain unchanged with T_A . Irreversibility in the ST, power cycle condenser, CT, OWH and MC1 of the power cycle decreases while it increases in the MC3, BFPs, CTPs, generator, solution pump and significantly in the SHE and the absorber. The gain in irreversibility is more than the reduction; hence the total of all components' irreversibility is more at higher T_A .

It is found that the combined power cycle and the VARS produces the best energetic and exergetic performance at boiler pressure of 150 bar and VARS generator temperature of 80°C. These two operating parameters can be chosen for the maximum performance along with the VARS condenser and absorber temperature both maintained at 35 °C to keep the irreversible losses at the minimum. It is better to take higher values of evaporator temperature for improved performance; however the limiting value will depend upon the source temperature supplying the heat to the evaporator. Higher cooling capacity means more cooling but at the same time it causes reduction in net power as explained in chapter 3. Irreversibility distribution among the various components of the combined system shows a major percentage of losses take place in the flue gas exhaust leaving the boiler and the boiler. The high flue gas exhaust exergy implies possibility of further utilizing this high temperature exhaust gas stream for some other useful purpose. Among the VARS components the generator produced the maximum irreversibility followed by irreversibility contribution by the absorber, condenser, evaporator and the SHE.

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