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Thermodynamic analysis of a 500 MW_e coal-fired supercritical power plant with CO_2 capture integrated with Kalina cycle for combined cooling and power

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A thermodynamic study is carried out on a 500 MW_e coal based supercritical thermal power plant (base plant) with Mono Ethanol Amine (MEA) based CO_2 capture unit integrated with a Kalina cycle (Low-grade energy cycle) setup for Combined Cooling and Power (CCP) generation using Indian High Ash (HA) coal as fuel, and the results are compared with an imported Low Ash (LA) coal. The modelling and simulation of the different plant configurations are done by using the simulation software "Cycle-Tempo". The base plant is integrated with the CO_2 capture unit working on MEA based post combustion carbon capture technique. The separated CO_2 is compressed to a pressure and temperature of 110 bar and 35°C, respectively for ease of transportation and storage. During the four-stage CO_2 compression the heat wasted through the intercoolers is utilized by using Kalina cycle system. In Kalina cycle binary mixture of ammonia-water (NH_3-H_2O) is used as a working fluid. This mixture passes through the intercoolers of the CO_2 compression system and got vaporized by utilizing the waste heat. Thereafter, the vapour passes through the two-stage turbines with reheater resulting in additional power generation. The mixture is throttled after the condenser produces the cooling effect. There is about 1.72% of energy efficiency improvement of the proposed integrated plant in comparison with the base plant with CO_2 capture. There is about 1.7 MW of additional electricity generation along with 5.7 MW of cooling effect (equivalent to 1632 TR) are obtained by this novel technique.

Keywords: Supercritical power plant, Kalina cycle, CO_2 capture, Combined Cooling and Power (CCP).

Introduction

Fossil fuels are the dominant sources of energy which include coal, petroleum, natural gas etc. Coal is the largest abundant source of energy on the planet, but it generates lots of greenhouse gases. It has been projected that around 3084 million tonnes of CO_2 emission rise in India will take place by 2030, out of which 43% of CO_2 will be emitted from the pulverized coal-based power plants[1]. Moreover, the study says that the emission of CO_2 from all the existing coal fleet across the world would emit a cumulative 175 Giga tonnes of CO_2 by 2040 equivalent to 5 times of the total energy sector emissions in 2018[2]. Such a huge amount of CO_2 emission will deteriorate our environment; hence there is a dire need for novel technologies to limit or avoid the CO_2 emissions. The widely used techniques for the capturing of CO_2 are pre-combustion carbon capture, post-combustion carbon capture and oxy-fuel combustion capture. CO_2 capturing through pre-combustion technique is done prior to the combustion of fuel and hence, it is a less energy intensive process as compared to post combustion techniques. In post combustion process the CO_2 which is captured after combustion of fuel is done by physical or chemical adsorption or absorption processes and also by using membranes. In oxy-fuel combustion carbon capture technique, oxygen is supplied in the combustor resulting in high concentrated CO_2 emission, hence capture of CO_2 becomes easy. But this process is not economically feasible because lots of energy is required to produce O_2 through Air Separation Unit (ASU)[3,4]. Comparative studies show that Mono Ethanol Amine (MEA) based chemical absorption process is the most economical and popular CO_2 capture technique due to high CO_2 capturing efficiency[5]. The CO_2 capture drops the plant efficiency significantly. The process heat available from CO_2 capture unit can be utilized for running low grade cycles. Some of the low grade cycles are Kalina cycle, Organic Rankine Cycle (ORC), CO_2 transcritical power cycle etc. out of which ORC system is one of the suitable cycles for waste heat recovery at low temperature because each process is optimal at different operating ranges of the cycle. But due to low temperature range the overall efficiency of this cycle is poor[6]. In contrast, Kalina cycle plays an important role for waste heat recovery because it is very efficient technology for low grade waste heat power generation[7]. Zhang *et al.* are carried out an analysis based on energy and exergy of a cogeneration plant between ORC and absorption heat pump, where waste heat are recovered from the exhaust of the steam turbine and the result shows that there is an increase in energy efficiency by 9.38% and 1.71% of exergy efficiency[8]. Campos *et al.* have done the thermo-economic optimization on the ORC, and the cycle is used to recover the waste heat of flue gas from the micro gas turbine and the result shows an additional electrical power generation of 14.1 kW[9]. Özahi *et al.* are carried out an optimization on Kalina cycle added with an municipal solid waste based power plant running based on the waste heat from the exhaust gas and the result shows that there is an improvement in efficiency of 3.62%[10]. Abam *et al.* did the thermodynamic and economic analyses of a Kalina cycle integrated with an absorption refrigeration system for Combined Cooling and Power (CCP) production resulting in 1077 kW of cooling effect[11].

Advantages of using a Kalina cycle instead of ORC is that it uses a mixture of ammonia and water which possess variable boiling temperatures. Another major advantage being lesser irreversibilities associated during heat transfer process. It also has a lower Ozone Depletion Potential (ODP) and has efficient thermo-physical properties[12]. Due to its higher efficiency, Kalina cycle is chosen for utilizing the waste heat coming from the intercoolers of the CO_2 capture unit.

In the present study, a thermodynamic analysis is carried out for a 500 MW_e supercritical power plant with Kalina cycle integrated CO_2 capture unit for CCP. MEA based post combustion CO_2 capture technique is used for capturing CO_2. After the extraction of CO_2, it is compressed to reach into the supercritical state for ease of transportation and storage. During the compression process, there is a rise in temperature in the intercoolers used in the CO_2 compression system. The waste heat generated from the intercoolers is utilized in Kalina cycle for additional power generation and getting the cooling effect.

Plant configurations

In our present work, a 500 MW_e supercritical power plant (Base plant) is considered as a stand alone plant with steam parameters of 242.2 bar/537°C/565°C. It has one stage reheating process[13] and after reheating, the final temperature of feed water is about 280°C. The plant having several types of turbine and feed water heaters which are one high pressure (HP) turbine, one intermediate pressure (IP) turbine and two low pressure (LP) turbine, three HP feed water heaters and four LP feed water heaters. This base plant is integrated with CO_2 capture unit, in the CO_2 capture unit the flue gas from the air pre-heater is passed through the moisture separator wherein moisture is separated by condensation. Then the flue gas is passed through the CO_2 separator, where flue gas and solvent (MEA) flow in opposite direction. During this process, CO_2 gets absorbed by the solvent. The rich MEA is passed through the reboiler where the absorbed CO_2 is separated out; the energy required for the regeneration is provided by the steam. The required steam is bleed from the line between IP turbine and LP turbine and from the reboiler the steam is again feedback to the LP feed water heater. Since huge amount heat is being extracted so it reduces the efficiencies. After the separation, the CO_2 is compressed to a particular pressure and temperature (110 bar and 35°C) to reach into supercritical state[14], for which four stage intercooler is required to compressed the CO_2 at that point. The schematic of base plant added with CO_2 capture unit is shown in Fig. 1.

In the proposed plant configuration, Kalina cycle is integrated with CO_2 capture unit of the plant for utilizing the waste heat, which is being available at intercooler of CO_2 compression process. After the expansion process from two stage turbines in the Kalina cycle, the working fluid goes through the condenser after that one throttle valve is added for decreasing the temperature and the lower temperature working fluid then passes through the heat sink where heat extraction will take place from the coolant space. Then, the working fluid passes through the drum where the separation of liquid and gaseous form takes place. The liquid form of working fluid is sent back to the intercooler of CO_2 compression process. After the absorption of heat, it is converted into vapor form and sent to the turbine and the process contin-

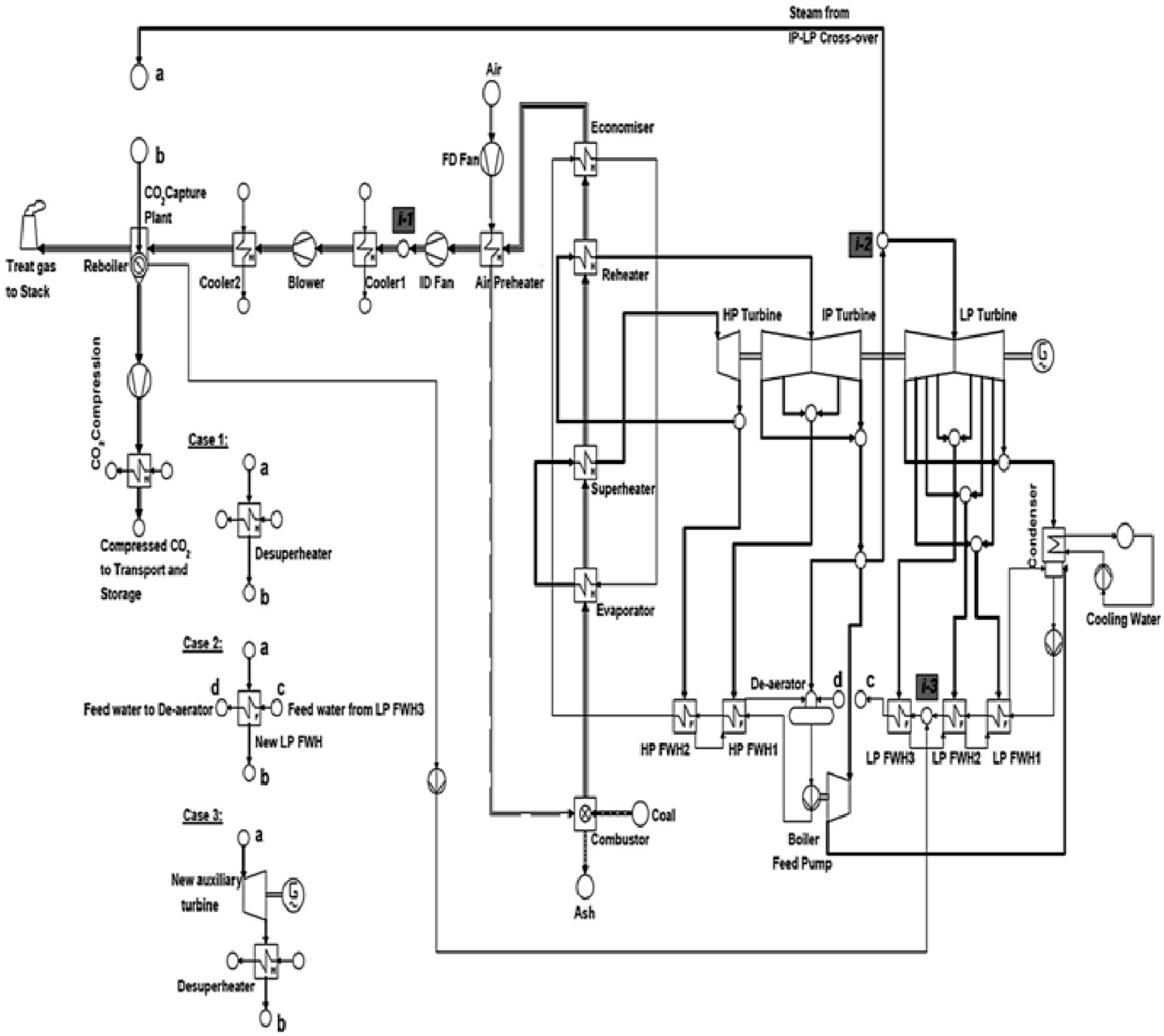

Fig. 1. Base plant with CO_2 capture unit[14].

ues. The schematic of Kalina system integrated with the intercooler of CO_2 capture unit is shown in Fig. 2.

Methodologies

Thermodynamic analysis of the proposed model is performed using commercially available software called 'CYCLE-TEMPO'[15]. The software performs the mass, species, energy and exergy balance across all the components of the plant using the following governing equations:

(a) Mass balance:

$$\Sigma_i \dot{m}_i = \Sigma_o \dot{m}_o$$

(b) Energy balance:

$$\Sigma_i \dot{m}_i h_i + \dot{Q}_{cv} = \Sigma_o \dot{m}_o h_o + \dot{W}_{cv}$$

(c) Exergy balance:

$$\Sigma_i \dot{m}_i \Psi_i + \dot{X}_{heat} = \Sigma_o \dot{m}_o \Psi_o + \dot{W}_{cv} + \dot{I}$$

(d) Chemical species balance:

$$\Sigma_o \dot{N}_j = \Sigma_i \dot{N}_j + \dot{N}_p$$

The various components of the plant are drawn and connected using appropriate chosen streams available from the

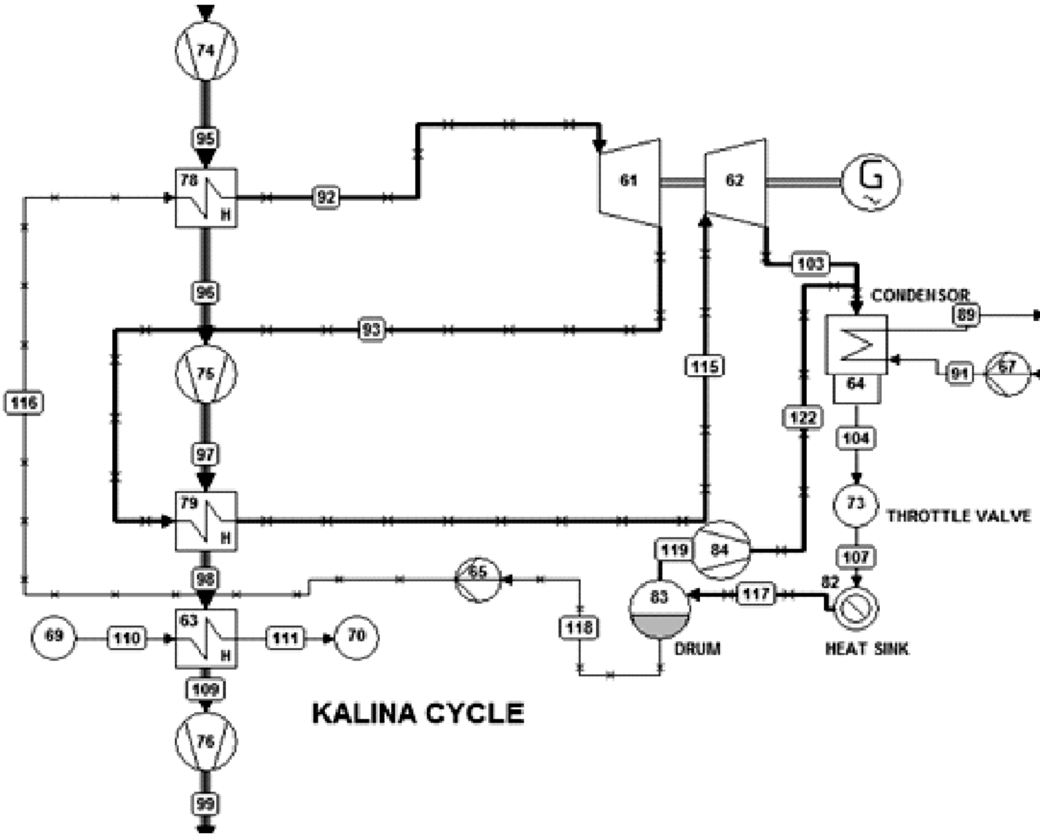

Fig. 2. Kalina cycle integrated with CO_2 capture unit.

components/fuel stream library available in the software.

The component modelling starts with process flow diagram of the power plant followed by specifying different operating conditions for all individual components like pressure, temperature, flow rate at inlet/outlet, efficiencies of compressor, pump, motor.

Fuel characteristics

The Indian coal considered as fuel is of high quality and low graded coal because of its low sulphur content and high mineral content. Hence, this coal is called as HA coal. Because of HA and low carbon content, Indian coal has a lower heating value. In this analysis the Higher Heating Value of HA coal and LA coal are estimated as 15.83 MJ/kg and 27.42 MJ/kg based on as dry basis. The characteristics of coal are given in Table 1.

Table 1. Coal characteristics[13]

	Indian high ash coal Dry basis (wt%)	Imported low ash coal Dry basis (wt%)
Proximate analysis:		
Fixed carbon	27.27	60.47
Volatile matter	23.96	22.85
Ash	48.87	16.68
Ultimate analysis:		
Carbon	39.16	69.8
Hydrogen	2.76	3.58
Oxygen (by difference)	7.92	7.66
Nitrogen	0.78	1.73
Sulphur	0.51	0.55
Ash	48.87	16.68

Performance parameters

There are following parameters based upon that the calculation part has done:

(i) Energy efficiency (η) of the plant

$$= \frac{\text{Net power output of the plant}}{\text{Mass flow rate of the coal} \times \text{Higher heating value of coal}}$$

(ii) Exergy efficiency (ε) of the plant

$$= \frac{\text{Net power output of the plant}}{\text{Mass flow rate of the coal} \times \text{Specific exergy of coal}}$$

(iii) Net efficiency with CCP

$$= \frac{\text{Net power output + Heat absorbed through the coolant space}}{\text{Mass flow rate of the coal} \times \text{Higher heating value of coal}}$$

Assumptions

Following assumptions are given below based upon that the thermodynamic analysis has done:

(i) On the basis of Indian climatic condition the relative humidity, temperature and pressure are 60%, 33°C and 1.013 bar, and the composition of air is (in mole%) Nitrogen = 75.62, Oxygen = 20.30, Water = 3.12, Carbon dioxide = 0.03, Sulphur dioxide = 0.01, others = 0.92.

(ii) 7.5% of total energy production is assumed to be the auxiliary power consumption of the Supercritical power plant.

(iii) Recovery of CO_2 is 85% with 98% of CO_2 purity.

(iv) The efficiency of the pumps is 85%.

(v) Rich and weak ammonia-water mixtures are saturated at the exit of the separator.

Results and discussion

There is a comparison of efficiencies between the base plant with CO_2 capture and the proposed model based on HA and LA coal, that are presented on Table 2 and Table 3.

From the analysis, it has been seen that there is a significant difference in energy efficiency and exergy efficiency for LA coal as compared with HA coal.

It is observed that in the proposed model, by utilizing the waste heat there is some increment in efficiency compared with the existing power plant with CO_2 capture unit.

Table 2. Efficiencies of the plant with CO_2 capture

Plant efficiency (%)	High ash coal	Low ash coal
Energy efficiency	28.41	29.52
Exergy efficiency	25.02	27.64

Table 3. Efficiencies of the proposed model

Plant efficiency (%)	High ash coal	Low ash coal
Energy efficiency	28.90	30.09
Exergy efficiency	25.10	27.80

Energy balance of the proposed model:

The energy balance of the proposed model is given in Table 4. It tells about quantity-wise losses of different components. The losses are calculated by the ratio between the losses of energy through the component and the heat energy input from the coal. It shows that maximum heat rejection occurs at the condenser. In this power plant, there is an additional loss of energy in flue gas cooling before entering into the separation unit, which is near about 6.22% for HA coal and about 5.09% for LA coal. Some part of energy is utilised in the compression of CO_2.

Table 4. Energy balance of the proposed model

Components (%)	High ash coal	Low ash coal
Energy efficiency of plant	27.81	29.24
Condenser	21.99	22.09
Heat loss in steam cooling for MEA regeneration	29.96	30.09
Bottom ash	0.84	0.70
Heat rejected through stack	2.92	3.75
Combustor	1.44	1.53
Heat loss during flue gas cooling	6.22	5.09
Heat loss during intercooling in compressors	3.18	3.21
Heat loss in cooling water (Kalina cycle condenser)	1.43	1.49
Other losses (by difference)	4.17	2.78

Exergy balance of the proposed model:

The exergy balance using two types of coal is shown in the Table 5. It tells about quality-wise losses at a different component of the plant, and it reveals that in the combustor losses are very high because of the irreversibility during the heat transfer and combustion process. The maximum losses occur in the combustor. The exergy destructions in CO_2 compression is 5.40% for HA coal and 5.76% for LA coal.

Parametric analysis of the proposed model:

A sensitivity analysis is done to study the impact of pressure on the energy efficiency of the plant and it is shown in Fig. 3. It is found in Fig. 3 that work output from Kalina cycle shows an increasing trend corresponding to the rise in inlet pressure of the first turbine.

Table 5. Exergy balance of proposed model

Components (%)	High ash coal	Low ash coal
Exergy efficiency	25.10	27.80
Losses in combustor	33.54	28.64
Loss in steam generation (Excluding combustor)	17.7	19.22
Turbines	2.57	2.71
Stack	0.91	1.57
Condenser and cooling water	0.97	1.03
Loss in steam cooling for MEA regeneration	6.64	7.02
Compressed CO_2 stream	5.37	5.76
Heat exchangers	1.54	1.63
Compressors	0.7	0.78
Ash	0.47	0.41
Other losses (by difference)	4.49	3.42

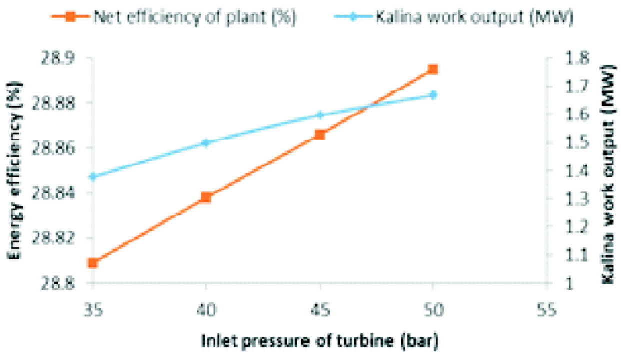

Fig. 3. Effect of inlet pressure on Kalina work output and Net efficiency of plant for HA coal.

A parametric study on the efficiency of the plant with the mass fraction of ammonia is also shown in Fig. 4. It is observed that efficiency increases with an increase in ammonia mass fraction in the working fluid of Kalina cycle as higher ammonia fraction causes lower boiling temperature at fixed pressure that helps to reduce irreversibility in the heat exchanger and produce more vapor mass flow rate.

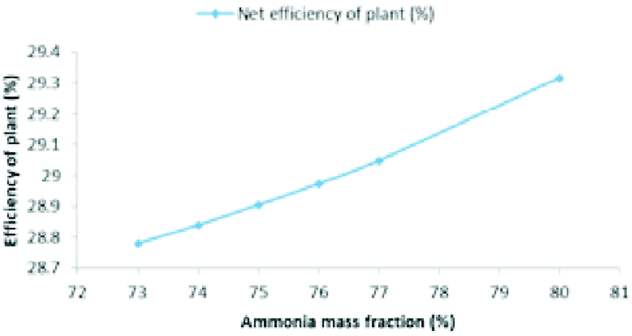

Fig. 4. Effect of mass fraction of ammonia on Net efficiency of plant for HA coal.

Similarly, for LA coal feed power plant, sensitivity analysis on the energy efficiency of the plant is also studied. The work output from Kalina cycle shows an increasing trend corresponding to the rise in inlet pressure of the first turbine as shown in Fig. 5, whereas the parametric study on efficiency of the plant with the ammonia mass fraction is shown in Fig. 6. It is observed that efficiency increases with increase in ammonia mass fraction in the working fluid of Kalina cycle.

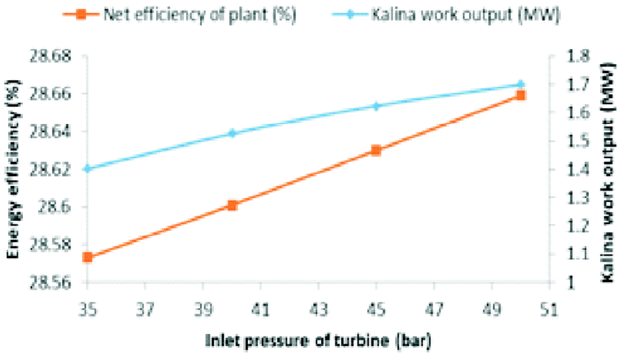

Fig. 5. Effect of pressure on Kalina work output and Net efficiency of plant for LA coal.

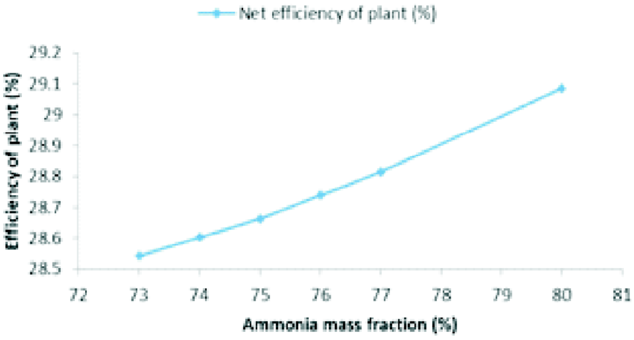

Fig. 6. Effect of NH_3 mass fraction on Net efficiency of plant for LA coal.

Additional power generation and cooling effect:

The Kalina cycle integrated CO_2 capture unit with the base plant helps in producing about 1.7 MW of additional electricity along with 5.7 MW of cooling effect which is equivalent to 1632 ton of Refrigeration (TR).

Conclusions

From the thermodynamic analysis of the proposed model, the following major conclusions are drawn:

(1) There is about 1.72% increase in energy efficiency and 0.31% increase in exergy efficiency as compared to the existing power plant with CO_2 capture due to additional power output and cooling effect.

(2) In energy balance, maximum losses occur in the condenser and also during MEA regeneration whereas, exergy balance shows maximum losses take place in the combustor.

(3) By increasing pressure at the inlet of Kalina cycle turbine, the efficiency and power output can be increased.

(4) With increasing ammonia mass fraction, the cycle efficiency can also increase.

(5) This novel technique delivers about 1.7 MW of additional electrical power and about 5.7 MW of cooling effect (equivalent to 1632 TR).

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