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Potential of Allam cycle with natural gas to reduce carbon dioxide emission in India

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Abstract

The utility electricity sector in India has one national grid with an installed capacity of 330.86 GW as on 31 December 2017, of which 66.2 % is fossil fuel based. The utility electricity sector in India emitted 2066.01 Mt CO_2 in 2015.

India is one of the fast-growing economies and power demand will also be high in future. India is also committed to reduce greenhouse gas emission level by 33 % in 2030 as compare to 2005. Allam cycle is newly developed complete green energy power cycle with nearly 60 % efficiency.

CO_2 emission from coal is 214.3 pounds, and 117 pounds from natural gas, per million British Thermal Unit (BTU). CO_2 emission is less in case of natural gas compare to coal.

This paper shows the thermodynamic analysis of natural gas based Allam cycle and NTPC (Dadri) combined gas power plant. This paper also shows the comparison of thermal efficiency, exergy destruction in all component for both cycles.

This paper also highlights the possibility of reduction in CO_2 emission by newly developed Allam power cycle. Thermodynamic analysis is done by using EES (Engineering equation solver) and REFPROP linked with Excel.

Introduction

India has 96 Tcf technically recoverable shale gas according to the report EIA (2015). IEA (2015) has published a report on the NET power cycle and describe all technical information relevant to natural gas fired ALLAM cycle. The 54.2% overall thermodynamic efficiency is shown in IEAGHG report which is 10% higher than combine gas power plant with 100% carbon capturing and storage. Currently, India has total 25 GW electricity generation using combine gas power plant. The present study focused on the exergetic efficiency calculation and comparison of Dadri gas power plant and ALLAM power cycle for 640 MW gross electricity generation.

This paper presents four following section:

(1) Introduction part explains complete layout of ALLAM power cycle and DADRI combine gas power plant with all state points of pressure and temperature.
(2) In second part, describes the methodology to perform irreversibility and efficiency calculation for each component for both cycle. Second part also includes the calculation of CO_2 emission for both cycle.
(3) Third section is result and discussion which compare the irreversibility of each component and analyse the CO_2 emission level.
(4) In final section, conclusion has been done on the basis on comparative study.

The objective of this study is to analyse the CO_2 reduction due to Allam cycle as compared to combine gas power plant for 640 MWe turbine power output.

Dadri Gas Power Plant

NTPC (National Thermal Power Corporation) was set up in the central sector in the 1975. Only PSU (Public Sector Unit) to achieve excellent rating in respect of MOU (Millions of Unit) targets signed with Government of India each year. It is a combine gas plant in which 520 MW (130*4, Nos) power generated by gas turbine and 120 MW produced by steam turbine as a bottoming cycle. The turbine’s exhaust-gas goes to a heat recovery steam generator to generate superheated steam. That steam is utilized in a standard steam power cycle, which consists of a turbine, a condenser and a pump). Both the gas and steam turbines drive electric generators.

NTPC Dadri has both coal and gas fired thermal power plant based in Uttar Pradesh, India. In this paper, combined gas power plant has been analysed.

ALLAM Cycle Description

The NET Power cycle utilizes carbon dioxide as the working fluid in a high-pressure, low-pressure-ratio Brayton cycle, operating with a single turbine that has an inlet pressure around 300 bar and pressure ratio around 9. The high-pressure combustor burns natural gas in an oxidant stream resulting from the mixture of high-purity oxygen stream with the recycle gas stream and provides the feed to a direct-fired CO_2 turbine. A regenerative heat exchanger transfers heat from the high temperature turbine exhaust to the high pressure recycle required to control the combustion temperature and cool the turbine blades. Heat from the hot air from the ASU main air compressor is recovered in the regenerative exchanger to enhance the cycle efficiency.

Main Feature of ALLAM Cycle

(1) Oxygen purity is 99.5% by mole using cryogenic distillation of atmospheric air and produced around 110 bar.
(2) There are total four stages in recompression with intercooler in each stage.
(3) The required temperature of cooling stream in turbine is less than 400 ^oC.
(4) The mass flow rate of oxygen is 3 % excess of stoichiometric ratio to lead proper combustion. Use of pure oxygen (99.5%) instead of air in combustion resulted in 97% CO_2 at combustion outlet.
(5) The whole amount of CO_2 generated in combustion is completely captured without any further purification because of the lower oxygen excess required in combustion for natural gas. Natural gas is clean gas comparatively gasified coal.

Methodology

Thermodynamic Analysis

To perform the thermodynamic analysis, thermophysical property like enthalpy and entropy need to define. Exergy destruction in each component is calculated for both cases.

(1) Analysis of NTPC Dadri Combine gas power plant:

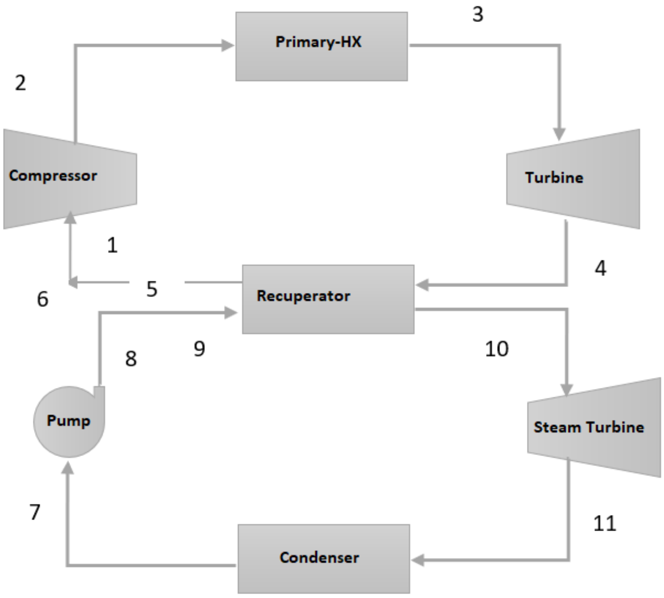

Figure 1: Schematic layout of NTPC Dadri combine plant

Table 1: Pressure and Temperature at each state point

State	1	2	3	4	5	6
P, Bar	1	10	9.7	1.053	1.053	1
T, K	298	619	1673	1019	573.6	475.1

State	7	8	9	10	11
P, Bar	0.8864	60	60	60	0.8864
T, K	300	305	443.4	773	369.4

The temperature of gases after leaving from gas turbine is given by

$$T_4 = T_3 * \left(\frac{1}{r_{pg}}\right)^{(\Upsilon_g-1)*\eta_{gt}/\Upsilon_g} \quad \text{Where, } r_{pg} = P_3/P_4 \tag{1}$$

The temperature of air after leaving the compressor

$$T_2 = T_1 * \left(\frac{1}{r_{pc}}\right)^{(\Upsilon_a-1)/(\eta_c*\Upsilon_a)} \quad \text{Where, } r_{pc} = P_2/P_1 \tag{2}$$

The relation between gas turbine and compressor pressure ratio is

$$r_{pg} = (1 - \beta_1) * (1 - \beta_2) * r_{pc} \quad (3)$$

where β1 and β2 is percentage pressure drop in combustion chamber and HRSG respectively. If the flow rate of combustion gas be 1 kg/s and that of fuel is f kg/s then, the flow of air= (1-f) kg/s and flow of fuel is given by

$$f = (C_{pg} * T_3 - C_{pa} * T_2)/(CV - C_{pa} * T_2) \quad (4)$$

Air-fuel ratio = (1-f)/f

- Pinch point temperature difference (T_5 – T_f) = 25 ^oC
- T_f = $(T\_sat)_{60\ bar}$ = 275.64 ^oC

Mass flow rate of steam can be calculated as

$$w_s = C_{pg} * (T_4 - T_5)/(h_a - h_f) \quad (5)$$

Where, $w_s = m_s/m_g$

The mass flow rate of air in compressor is

$$m_a = (1 - f) * m_g \quad (6)$$

The mass flow rate of fuel in combustion chamber is

$$m_f = f * m_g \quad (7)$$

(1) Overall thermal efficiency can be defined as

- $\eta_{th} = \frac{Wnet}{Heat\ Supplied}$;

$$\text{Wnet} = P_{gas\ turbine} + P_{steam\ turbine} - P_{compressor} - P_{pump}$$

- Heat Supplied = M_f*CV

Table 2: Overall performance of NTPC Dadri

Mass flow rate calculated			
(1)	Natural gas flow rate	Kg/s	20.91
(2)	Air mass flow rate	Kg/s	645.5
(3)	Steam flow rate	Kg/s	154.2
Overall Performance			
(4)	Gas Turbine power output	MWe	520
(5)	Air Compressor power input	MWe	212.524
(6)	Steam turbine power output	MWe	120
(7)	Calorific Value	kJ/kg	42000
(8)	Thermal efficiency	%	48.17

(ii) Second law analysis: Energy conservation concept (or the first law of thermodynamics) does not give the detailed analysis of the losses in power plant components. It is necessary to pinpoint the exergy losses. Exergy analysis enables one to determine the maximum work that can be expected from energy device or process; this is possible because the second law expresses the quality of energy.

Exergy destruction calculation:

- Exergy_in = M*((H_in – H_o) – T_o*(S_in – S_o))
- Exergy_out = M*((H_out – H_o) – T_o*(S_out – S_o))
- I = Ex_in – E_out

Second law efficiency can be defined as

$$\eta_{II} = (Exergy_{supplied} - W\_net)/Exergy_{supplied}$$

- $Exergy_{supplied}$ = Heat Supplied * η_{carnot}

Table 3: Exergy Destruction and second law efficiency result

Exergy Calculation			
(1)	Exergy Supplied	MW	721.871
Exergy Destroyed in Component			
(2)	Gas Turbine	MW	12.5
(3)	Compressor	MW	14.1
(4)	Combustor	MW	250.662
(5)	Condenser	MW	69.522
(6)	Heat recovery steam generation	MW	51.39
(7)	Steam Turbine	MW	21.1
Second Law Efficiency			
(8)	Second Law Efficiency	%	58.61

(2) Analysis for Allam Cycle: All transport properties are calculated by invoking REFPROP database in the EXCEL software.

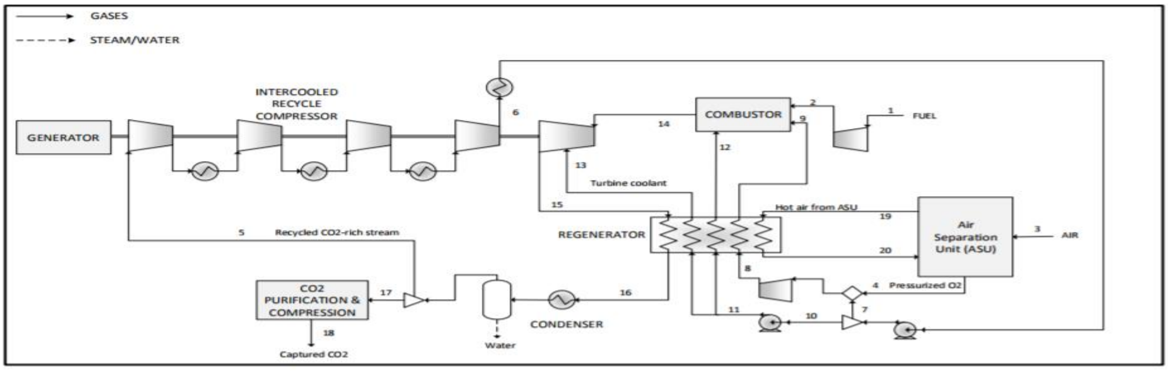

Figure 2: Allam Cycle layout (IEAGHG, 2015)

Composition of fluid at each state point is same as described for NET power in IEAGHG report.

Table 4: Temperature, Pressure and mass balance at each state point

State	1	2	3	4	5	6	7	8	9	10
P,Bar	70	305	1	110	33	80	110	305	303	110
T, K	288	418	300	288	302	316	299	318	993	299
Mass flow	16.97	16.97	283.99	63.22	1414.2	1414.2	566.7	629.96	629.96	801.81

State	11	12	13	14	15	16	17	18	19	20
P,Bar	305	303	303	300	34	33	33	110	7.5	7.3
T, K	323	993	673	1423	1013	328	302	303	548	328
Mass flow	801.88	652.75	149.06	1299.6	1448.7	1448.7	45.66	45.66	283.9	283.9

(1) Overall thermal efficiency can be defined as

- $\eta_{th} = \frac{Wnet}{Heat\ Supplied}$;

$$\text{Wnet} = P_{turbine} - P_{recycle\ compressor} - P_{recycle\ pump} - P_{natural\ gas\ compressor} - P_{oxidant\ stream\ compressor} - P_{ASU} - P_{coolant}$$

- Heat Supplied = M_f*CV

Table 5: Overall Performance Result

		Overall Performance	
1	Natural gas Flow rate	kg/s	16.97
2	Natural gas LHV	kJ/kg	46502
3	Turbine Power Output	MW	640
4	Recycle gas compression	MW	114.24
5	Natural gas compression input	MW	4.663
6	Air Separation Unit input Power	MW	87.82
7	Cooling water power consumption	MW	3.21
8	Total electrical power input	MW	209.933
9	Thermal efficiency	%	54.4
10	Total Water Consumption	kg/s	9105.2
11	Water condensed	Kg/s	34.33

Table 6: Exergy destroyed in each component and second law efficiency Result

Exergy calculation			
(1)	Exergy supplied	MW	622
Exergy destroyed in a component			
(2)	Turbine	MW	40.55
(3)	Compressor & pump	MW	30.009
(4)	Combustor	MW	91.9
(5)	Recuperator	MW	117.152
(6)	Condenser	MW	0.499
Second law Efficiency			
(7)	η_{II}	%	54.9

Impact of Allam cycle on CO_2 emission in India

The utility electricity sector in India has one National Grid with an installed capacity of 330.86 GW as on 31 December 2017 in which 66.2% is fossil fuel based. During the fiscal year 2016-17, the gross electricity generated by utilities in India was 1,236.39 TWh and the total electricity generation (utilities and non-utilities) in the country was 1,433.4 TWh. In 2015, 2066.01 MT CO2 was emitted from electricity generation in India.

In India total Gas Power Station installed Capacity is 25,329.38 MW which is 7.66 % of total installed power plant capacity. Electricity generation by gas in India in Fiscal Year 2016-17: 49,094 GWh, which is 4 % of total electricity generation. By using Allam power cycle for gas based power plant we can reduce CO_2 generation by 0.75 %.

Total electricity Generation in India = 1,236.39 TWh

Electricity from different fossil fuel is as follow

Electricity generation by gas = 49,094 GWh (4.0%)

Electricity generation by coal = 944,861 GWh (76.5%)

Electricity generation by diesel = 275 GWh (0.0%)

Total CO_2 Emission from fuel combustion = 2066.01 Mt

By Gas Based Power Plant CO_2 emission = 102 .02 Mt

If We Use Allam power Cycle Instead of gas combine power cycle, than CO_2 emission = 82.84 Mt CO_2

Percentage calculation of CO_2 emission reduction:

By Thermal power plant CO_2 emission is = 2066.01 Mt CO_2

Share of gas power plant = 4%

By Gas Based Power Plant CO_2 emission = 102 .02 Mt CO_2 (4.93% of total)

If We Use Allam power Cycle Instead of gas combine power cycle than CO_2 emission will reduce by,

= 19.18 Mt CO_2

= 0.93% of total CO_2 emission

Conclusion

In Allam Cycle Carbon dioxide is the main constituent of the working fluid and highly efficient for driving a turbine, when reaches to its supercritical state in the combustion unit. Energy losses from phase transitions of water can be avoided, which allows Allam cycle plants to recover more energy in their heat exchangers as compare to combined cycle plants. Thermal efficiency is 54.4 % of Allam cycle which 8% higher than NTPC Dadri combine gas power plant. Exergy destroyed in the recuperator is higher than combustor because more energy recovered from high temperature working fluid from exhaust of turbine.

The Study shows, 18.8 % (by mass) reduced fuel consumption in Allam cycle as compare to combined power generation cycle for gross power generation of 640 MW, that leads to 18.8% less CO_2 production. It is estimated that use of Allam power cycle for gas based power plant will reduce CO_2 generation by 0.93 % in India. As Allam Power Cycle being 100% carbon capturing process (Green Energy), CO_2 emission will reduce by 4.93% of total CO_2 emission.

Gas power plant installed Capacity is 25,329.38 MW in India, which is 7.66 % of total installed power capacity. Electricity generation by gas is 49,094 GWh in India as of Fiscal Year 2016-17, which is 4 % of total electricity generation.

Government of India has taken various measures to reduce environmental emissions of greenhouse gases from thermal power generation. If we convert all gas and coal based power plant to Allam power cycle, that will result in nearly 40 % - 44 % reduction in greenhouse gases emission.

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