Exergy Analysis of the Allam Cycle

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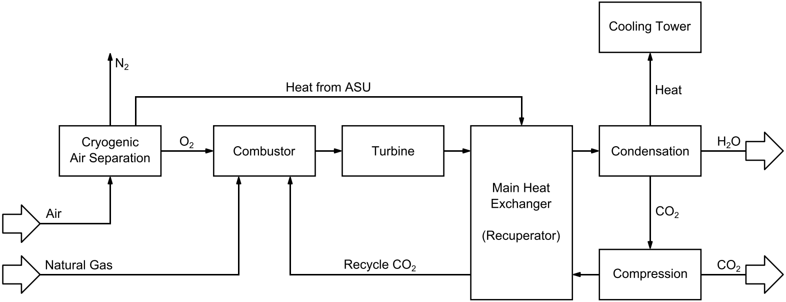
Contents

Introduction

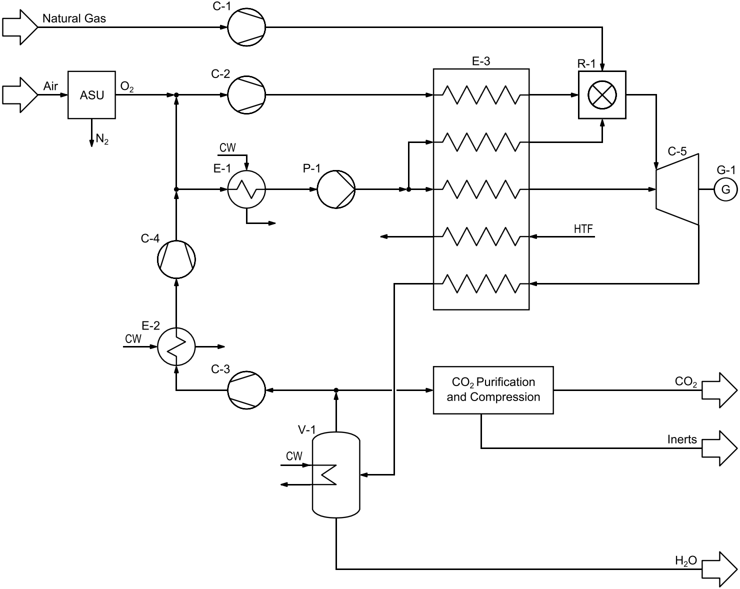
- Future power generation processes require CO_2 capture
- Technological options: post-combustion, pre-combustion, oxy-combustion
- Oxy-combustion facilitates the CO_2 capture
- High auxiliary power requirement for air separation (ASU)
- Traditional cycles are currently uneconomical
- Proposed Allam cycle recovers heat from ASU, reported efficiency of 59 % (LHV)
- Publicly available data is used for benchmarking the process by using conventional thermodynamic and exergy-based analysis methods
- Identification of main inefficiencies and possible improvement potential

System Description

- Allam cycle is single, highly recuperated, high-pressure and high-temperature gas turbine cycle
- CO_2 at high purity is the main working fluid
- Natural gas operation, combustion with pure oxygen from ASU
- High purity CO_2 purge stream for further processing



System Description – Aspen Plus Model



System Description – Simulation Assumptions

- Data is taken from the literature if available
- Unknown parameters are specified using best practice modeling and benchmark guidelines (DOE NETL, IEA)
- Property data: Peng-Robinson, Lee-Kessler-Plocker
- Environment conditions: Midwest-ISO
- Different technological levels: base case, high and low efficiency assumptions for screening study

Methodology – Conventional Thermodynamic Analysis

- Application of heat and mass balances
- Known principle: high-temperature heat source and low-temperature heat sink results in high efficiency
- Application is however limited to single product processes
- Captured CO_2 as a by-product complicates the analysis
- Benchmark process, evaluation of impact of CO_2 capture on process efficiency
- High influence of modeling assumptions, usage of quality and benchmark guidelines

Methodology – Exergy Analysis

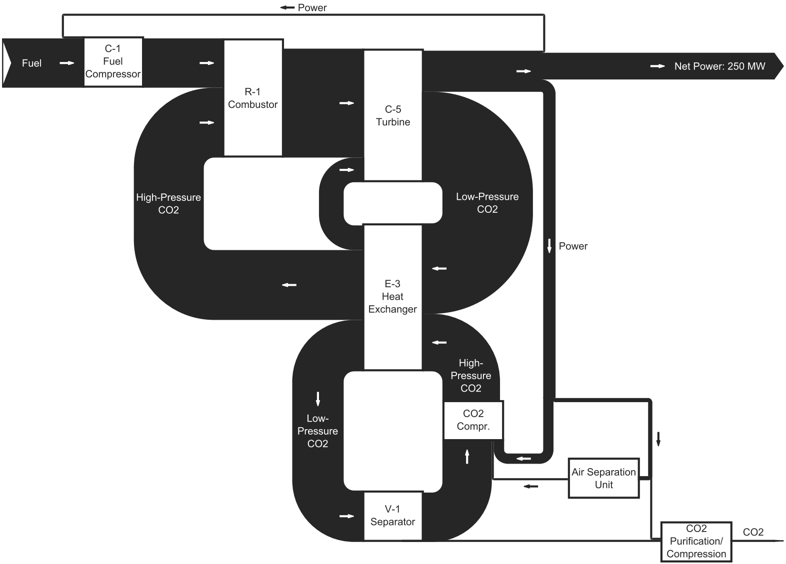
- Exergy is the maximum theoretical useful work obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment
- Exergy can be destroyed in contrast to energy
- Consideration of the different qualities of energy (heat, work)
- Environmental conditions are explicitly taken into account
- Quantification of the real thermodynamic losses
- Calculation of meaningful efficiencies
- Supports the design synthesis and improvement process
- Exergy destruction, exergetic efficiency, exergy destruction ratio

Results – Thermodynamic Analysis

Parameter		Simulation Study		
		Base Case	High Efficiency	Low Efficiency
Fuel Mass Flow Rate	[kg/s]	9.9	9.2	11.0
Gross Power	[MW]	292.1	280.7	307.3
Net Power	[MW]	250.0	250.0	250.0
Efficiency (LHV)	[%]	53.4	57.2	47.9

- The simulation model shows good agreement with literature data
- High efficiency case represents a possible configuration
- Model is highly dependent on recycle CO_2 recompression efficiency and pinch temperature differences
- Large interaction with ASU

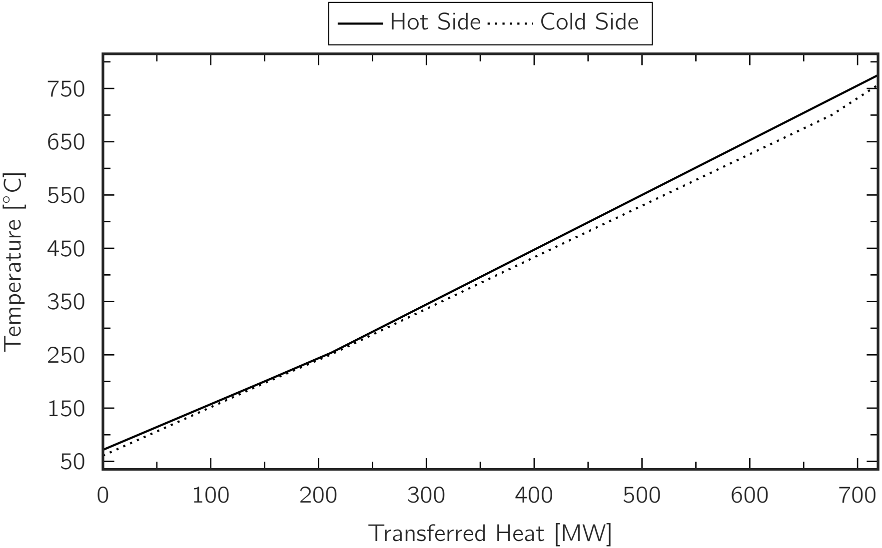
Results – Exergy Flow Diagram



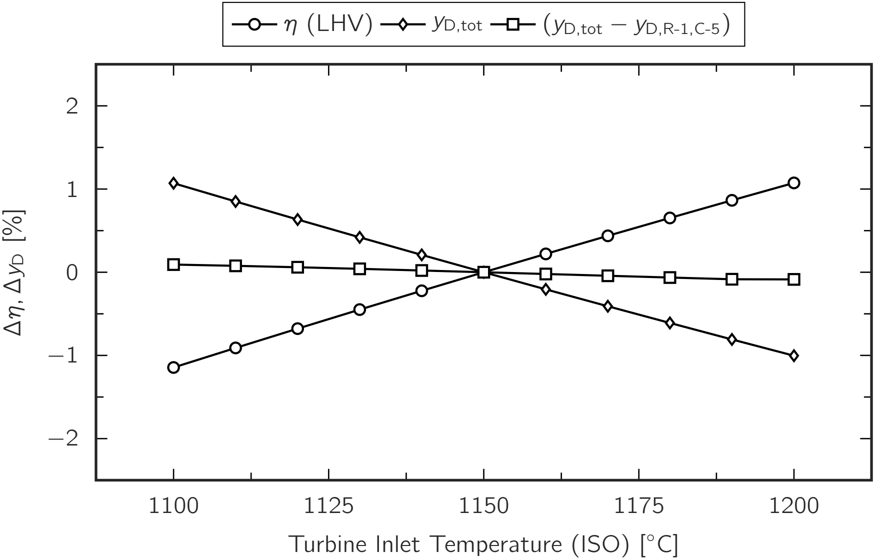
Results – Exergy Analysis

Simulation	Base Case			High Efficiency			Low Efficiency		
	$\dot{E}_D$	ε	y_D	$\dot{E}_D$	ε	y_D	$\dot{E}_D$	ε	y_D
Component	[MW]	[%]	[%]	[MW]	[%]	[%]	[MW]	[%]	[%]
C-1 Compressor	1.0	82.7	0.2	0.7	85.7	0.2	1.5	79.8	0.3
C-2 Compressor	11.0	56.9	2.3	8.2	50.1	1.8	15.4	67.2	2.8
C-3 Compressor	4.0	83.5	0.8	2.2	89.0	0.5	6.5	78.3	1.2
C-4 Compressor	5.0	77.9	1.0	3.4	82.0	0.7	7.3	73.8	1.3
C-5 Turbine	29.0	93.3	6.0	28.7	92.8	6.3	30.2	93.8	5.6
P-1 Pump	10.5	63.6	2.2	8.1	68.2	1.8	12.4	59.6	2.3
E-1 Heat Exchanger	5.4	32.2	1.1	4.9	34.8	1.1	5.5	29.5	1.0
E-2 Heat Exchanger	3.8	20.0	0.8	3.0	22.2	0.7	4.9	18.3	0.9
E-3 Heat Exchanger	11.8	96.9	2.4	11.4	96.8	2.5	16.7	96.1	3.1
R-1 Combustor	105.4	78.0	21.6	97.1	78.3	21.3	118.9	77.7	21.9
V-1 Separator	3.8	71.8	0.8	1.0	89.6	0.2	12.5	48.4	2.3
G-1 Generator	4.0	99.0	0.8	3.7	99.0	0.8	4.5	99.0	0.8
Auxiliary Units	19.7	53.1	4.0	11.2	63.5	2.5	30.6	46.6	5.6
Overall Cycle	214.4	51.3	44.0	183.6	54.9	40.4	266.9	46.0	49.1

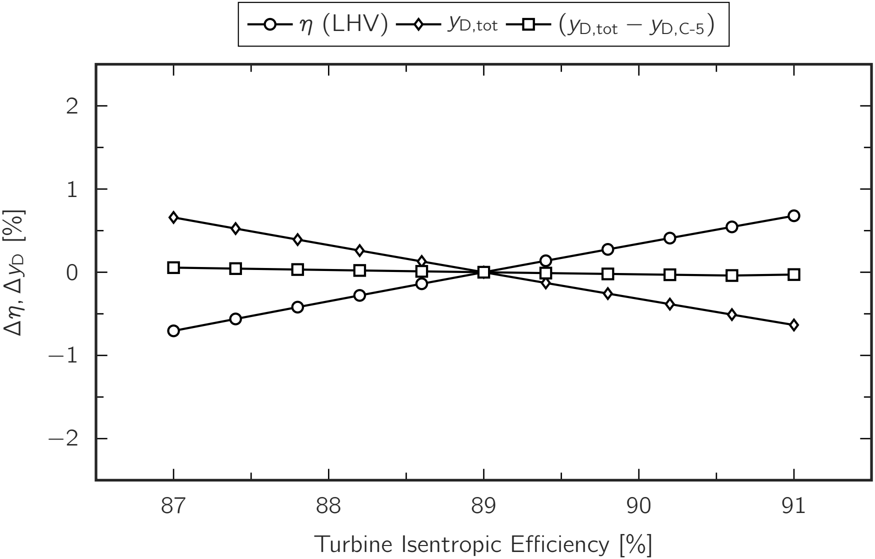
Results – Recuperator



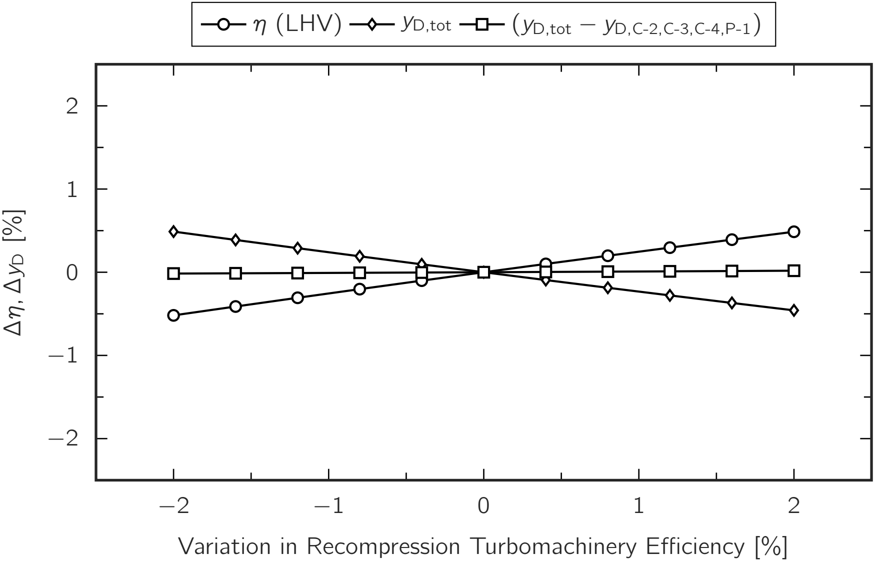
Results – Sensitivity Analysis: TIT (ISO)



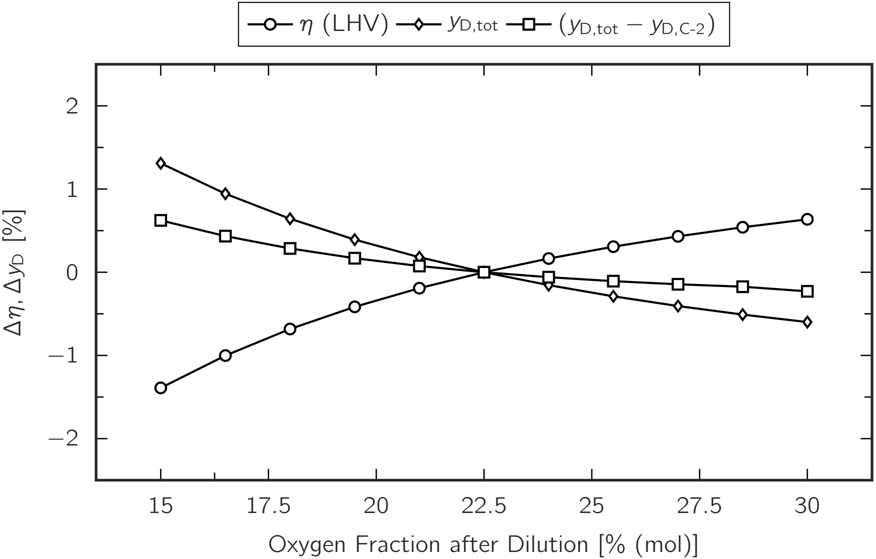
Results – Sensitivity Analysis: Turbine Efficiency



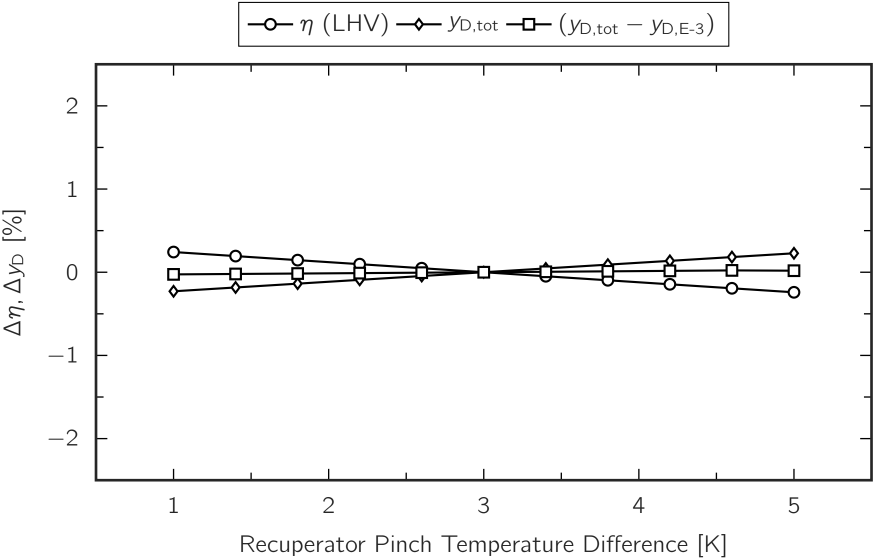
Results – Sensitivity Analysis: Recompression Efficiency



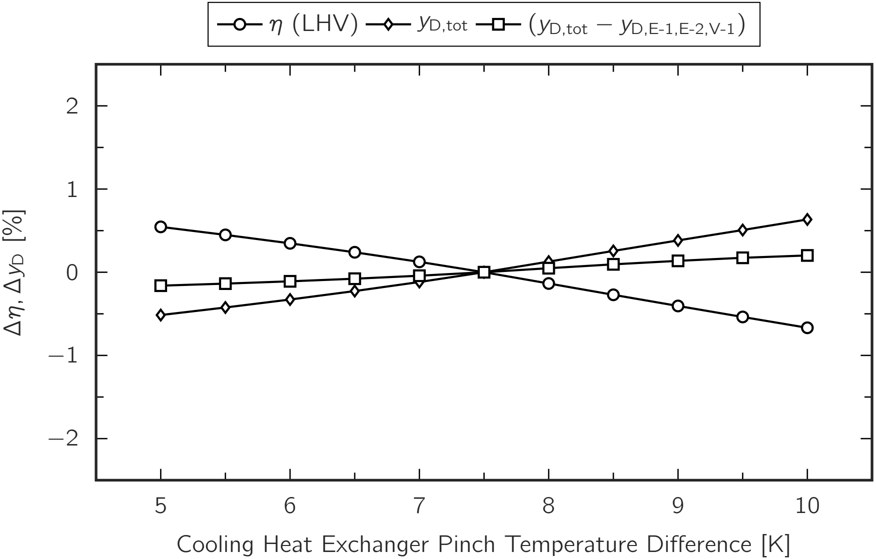
Results – Sensitivity Analysis: Dilution Oxygen Fraction



Results – Sensitivity Analysis: Recuperator



Results – Sensitivity Analysis: Coolers



Discussion

- High efficiency of the cycle at reasonable component parameterizations
- A certain component efficiency (turbomachinery, pinch temperature difference) is required for cycle to achieve high efficiencies
- Combustor, turbine, recuperator, CO_2 recompression and ASU have the highest exergy destruction
- Improvement potential is found considering the combustor-turbine section, recuperator and CO_2 recompression section
- Exergy analysis indicates that the recuperator effectively decouples the two pressure levels
- Exergetic efficiency/exergy destruction ratio of the main cycle components is comparable to other oxy-combustion cycles
- Cycle simplicity is a major advantage

Conclusions

- The Allam cycle is a promising cycle configuration to combine high-efficiency power generation with CO_2 capture
- Exergy analysis has shown that the largest inefficiencies are found within the main cycle
- Potential for improvement has been identified
- Study is a starting point for more detailed studies considering ASU and CO_2 purification and compression
- Exergy-based methods are to be further employed to understand the component interactions and the thermodynamic-economic implications.

Appendix – Midwest ISO and Exergy Model Definition

- Thermodynamic Environment

Site Conditions		Air Composition	
Model	Midwest ISO	Nitrogen (N_2)	0.7732 mol/mol
Ambient Pressure	1.01325 bar	Oxygen (O_2)	0.2074 mol/mol
Ambient Dry Bulb Temperature	15.0 °C	Argon (Ar)	0.0091 mol/mol
Ambient Wet Bulb Temperature	10.8 °C	Carbon Dioxide (CO_2)	0.0003 mol/mol
Relative Humidity	60 %	Water (H_2O)	0.0100 mol/mol
Cooling Water Temperature	15.6 °C	Molar Mass	28.854 kg/kmol

- Exergy Model (Thermodynamic Environment)

Ambient Temperature	15 °C
Ambient Pressure	1.01325 bar
Chemical exergy model	Szargut (1988)

Modeling Parameter Assumptions

Parameter		Base Case	Variation
Turbine Inlet Temperature (ISO)	°C	1150	± 0
Turbine Inlet Pressure	bar	300	± 0
Turbine Pressure Ratio	–	0.1	± 0
Combustor R-1, Outlet Temperature	°C	1300	± 100
Combustor R-1, Pressure Drop	%	1.6	± 0
Combustor R-1, Heat Loss	%	1.0	± 0
Oxygen Purity	%	99.5	± 0
Excess Oxygen	%	2.0	± 0
O_2 Fraction (Molar) after Dilution	%	22.5	± 7.5
Pump P-1, Efficiency	%	75	± 5
Pump P-1, Mechanical Efficiency	%	98	± 0
Compressor C-1-C-4, Polytropic Efficiency	%	80	± 5
Compressor C-1-C-4, Mechanical Efficiency	%	98	± 0
Motor Efficency	%	97	± 0
Generator G-1, Efficiency	%	99	± 0
Heat Exchanger E-1, E-2, Pinch Temperature Difference	K	7.5	± 2.5
Heat Exchanger E-1, E-2, Pressure Drop (gas)	%	2	± 0
Heat Exchanger E-1, E-2, Pressure Drop (liquid)	%	4	± 0
Heat Exchanger E-3, Pinch Temperature Difference	K	3	± 2
Heat Exchanger E-3, Pressure Drop	%	2	± 0
Separator V-1, Pressure Drop	%	2	± 0
Cooling Water Range	K	11	± 0
Cooling Tower Fan Power Demand	W/m^3_{Air}	197.5	± 0
ASU, Specific Power Demand	kWh/kg_{O2}	250	± 50
CO_2 Purification, Specific Power Demand	kWh/kg_{CO2}	50	± 25