Design Analysis of the Allam Cycle

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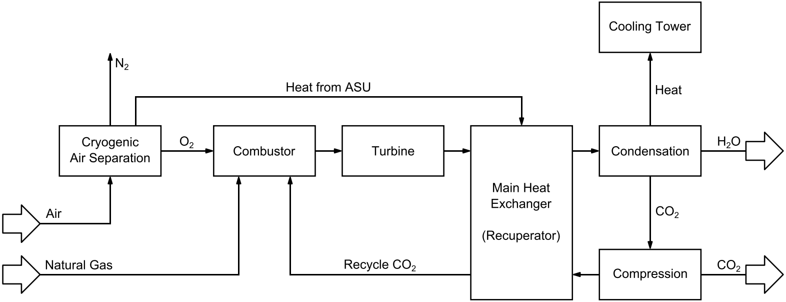
Contents

Introduction

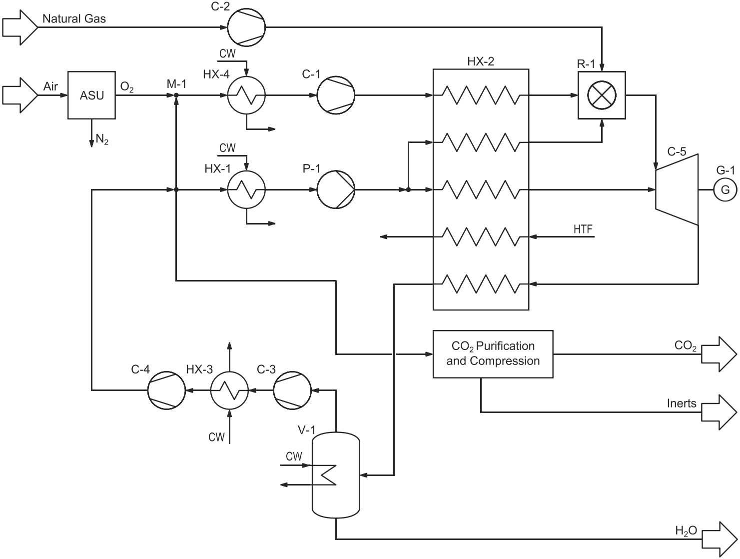
- Future power generation from fossil fuels require CO_2 capture
- Technological options: post-combustion, pre-combustion, oxy-combustion
- Oxy-combustion facilitates the CO_2 capture
- High auxiliary power requirement for air separation (ASU)
- Traditional cycles are currently uneconomical
- Proposed Allam cycle recovers heat from ASU, reported efficiency of 59 % (LHV_{CH4})
- Publicly disclosed data is used for benchmarking the process by using conventional thermodynamic and exergy-based analyses methods
- Identification of main inefficiencies, component interactions 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 for parameterization is taken from the literature if available
- Unknown parameters are specified using best practice modeling and benchmark guidelines (DOE NETL, IEA GHG)
- Property data: Peng-Robinson, Lee-Kesler-Plocker
- Environment conditions: US Midwest-ISO
- Different technological levels: base case, high and low efficiency assumptions for screening study

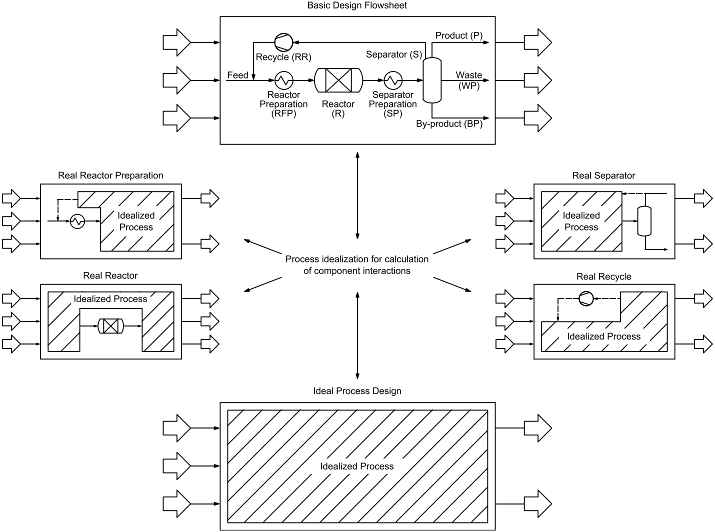
Methodology – Conventional Thermodynamic Analysis

- Application of energy 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 (high purity/pressure) is a by-product; complicating the analysis
- Benchmark process, evaluation of impact of CO_2 capture on process efficiency
- High influence of modeling assumptions, application 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
- Advanced Exergetic Analyses:
  - **Thermodynamic interactions among components (endogenous and exogenous)**
  - Real improvement potential of a component (avoidable and unavoidable)

Methodology – Advanced Exergetic Analysis

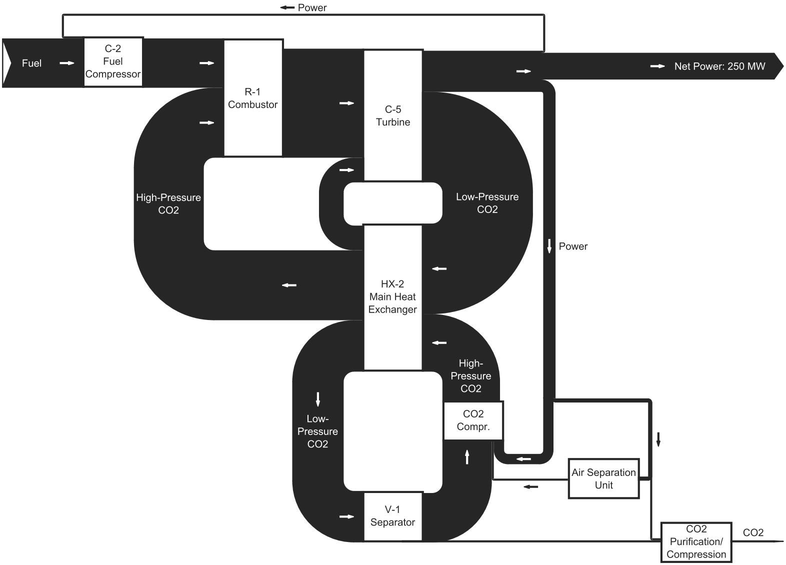


Results – Thermodynamic Analysis

Parameter		Simulation Study		
		Base Case	High Efficiency	Low Efficiency
Fuel Mass Flow Rate	[kg/s]	9.86	9.20	10.78
Gross Power	[MW]	293.3	283.8	305.1
Net Power	[MW]	250.0	250.0	250.0
Efficiency (LHV)	[%]	53.41	57.20	48.86

- The simulation model shows good agreement with literature data (Studies by Mancuso et al. 2015, Scaccabarozzi et al. 2016); simulation models are slightly different
- High efficiency case represents a possible configuration
- Model is highly dependent on recycle CO_2 recompression efficiency and pinch temperature differences
- Large power demand of the ASU

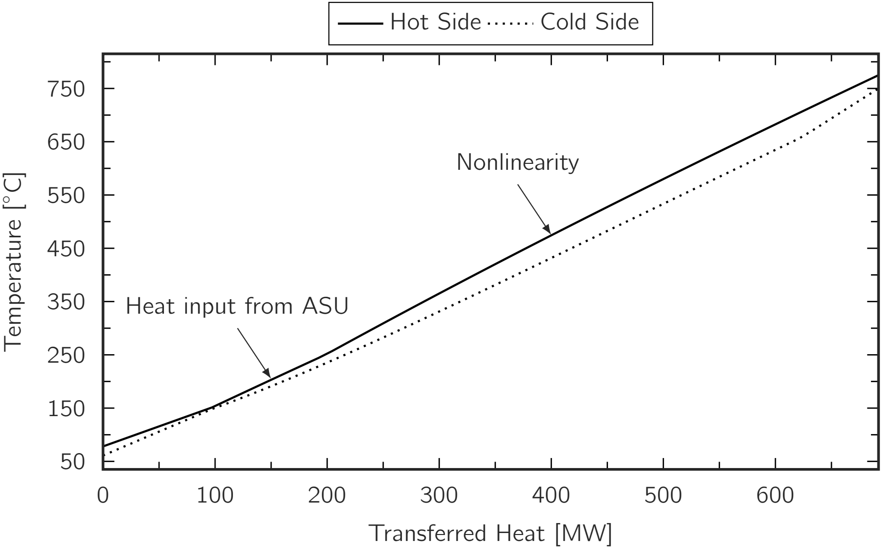
Results – Exergy Flow Diagram



Results – Exergy Analysis

Simulation		Base Case			High Efficiency			Low Efficiency		
		$\dot{E}_\mathrm{D}$	ε	y_D	$\dot{E}_\mathrm{D}$	ε	y_D	$\dot{E}_\mathrm{D}$	ε	y_D
Component		[MW]	[%]	[%]	[MW]	[%]	[%]	[MW]	[%]	[%]
C-1	Compressor	3.44	82.6	0.7	1.84	86.4	0.4	6.98	78.8	1.3
C-2	Compressor	0.83	84.4	0.2	0.57	87.7	0.1	1.18	81.3	0.2
C-3	Compressor	3.97	85.5	0.8	2.24	90.7	0.5	5.36	80.9	1.0
C-4	Compressor	3.34	80.0	0.7	2.11	84.4	0.5	5.99	76.0	1.1
C-5	Turbine	22.39	94.6	4.6	20.83	94.6	4.6	24.55	94.6	4.6
P-1	Pump	9.22	65.6	1.9	7.18	70.4	1.6	10.38	61.4	1.9
HX-1	HeatEx	6.48	9.3	1.3	6.08	10.1	1.3	6.81	8.1	1.3
HX-2	HeatEx	14.76	96.0	3.0	12.86	96.3	2.8	17.02	95.7	3.2
HX-3	HeatEx	5.66	5.6	1.2	4.92	6.2	1.1	5.50	5.4	1.0
HX-4	HeatEx	1.35	3.5	0.3	0.84	2.6	0.2	3.02	4.4	0.6
R-1	Combustor	108.69	77.3	22.3	102.36	77.1	22.5	117.31	77.6	22.0
V-1	Separator	7.21	55.2	1.5	3.79	68.4	0.8	14.36	40.7	2.7
G-1	Generator	3.93	99.0	0.8	3.67	99.0	0.8	4.29	99.0	0.8
M-1	Mixer	5.77	–	1.2	4.54	–	1.0	7.74	–	1.5
ASU	Air Sep.	8.26	68.8	1.7	1.27	86.8	0.3	16.45	57.1	3.1
CPU	CO2 Pur.	1.30	40.2	0.3	1.18	40.1	0.3	0.47	40.4	0.1
Overall Process		206.59	51.3	40.4	176.29	55.0	38.3	247.41	47.0	43.3

Results – Recuperator HX-2



Results – Advanced Exergy Analysis: Component Interactions

Simulation		Base Case				High Efficiency			
		$\dot{E}_{\mathrm{D}}$	$\dot{E}_{\mathrm{D}}^{\mathrm{EN}}$	$\dot{E}_{\mathrm{D}}^{\mathrm{EX}}$	$\frac{\dot{E}_{\mathrm{D}}^{\mathrm{EN}}}{\dot{E}_{\mathrm{D}}}$	$\dot{E}_{\mathrm{D}}$	$\dot{E}_{\mathrm{D}}^{\mathrm{EN}}$	$\dot{E}_{\mathrm{D}}^{\mathrm{EX}}$	$\frac{\dot{E}_{\mathrm{D}}^{\mathrm{EN}}}{\dot{E}_{\mathrm{D}}}$
Component		[MW]	[MW]	[MW]	[%]	[MW]	[MW]	[MW]	[%]
C-1	Compressor	3.44	0.28	3.16	8.10	1.84	0.23	1.60	12.67
C-2	Compressor	0.83	0.41	0.42	49.24	0.57	0.30	0.27	52.76
C-3	Compressor	3.97	0.06	3.91	1.60	2.24	0.04	2.20	1.83
C-4	Compressor	3.34	0.06	3.29	1.72	2.11	0.04	2.07	1.83
C-5	Turbine	22.39	11.49	10.90	51.32	20.83	11.46	9.37	55.02
P-1	Pump	9.22	0.00	9.22	0.00	7.18	0.00	7.18	0.00
HX-1	HeatEx	6.48	0.00	6.48	0.00	6.08	0.00	6.08	0.00
HX-2	HeatEx	14.76	0.00	14.76	0.00	12.86	0.00	12.86	0.00
HX-3	HeatEx	5.66	0.00	5.66	0.00	4.92	0.00	4.92	0.00
HX-4	HeatEx	1.35	0.00	1.35	0.00	0.84	0.00	0.84	0.00
R-1	Combustor	108.69	67.95	40.74	62.51	102.36	68.78	33.58	67.20
V-1	Separator	7.21	0.12	7.10	1.65	3.79	0.07	3.72	1.90
G-1	Generator	3.93	2.53	1.41	64.22	3.67	2.53	1.15	68.74
M-1	Mixer	5.77	0.00	5.77	0.00	4.54	0.00	4.54	0.00
ASU	Air Sep.	8.26	4.17	4.08	50.54	1.27	0.70	0.57	55.03
CPU	CO2 Pur.	1.30	0.14	1.16	10.75	1.18	0.12	1.06	10.46
Overall Process		206.59	82.89	123.70	40.12	176.29	83.46	90.38	47.34

Results – Advanced Exergy Analysis: Combustor

Simulation		Base Case				High Efficiency			
		$\dot{E}^{\text{EX,R-1}}_{\text{D},i}$	$\frac{\dot{E}^{\text{EX,R-1}}_{\text{D},i}}{\dot{E}^{\text{EX}}_{\text{D},i}}$	$\dot{E}^{\text{EX,i}}_{\text{D},R-1}$	$\frac{\dot{E}^{\text{EX,i}}_{\text{D},R-1}}{\dot{E}^{\text{EX}}_{\text{D},R-1}}$	$\dot{E}^{\text{EX,R-1}}_{\text{D},i}$	$\frac{\dot{E}^{\text{EX,R-1}}_{\text{D},i}}{\dot{E}^{\text{EX}}_{\text{D},i}}$	$\dot{E}^{\text{EX,i}}_{\text{D},R-1}$	$\frac{\dot{E}^{\text{EX,i}}_{\text{D},R-1}}{\dot{E}^{\text{EX}}_{\text{D},R-1}}$
Component		[MW]	[%]	[MW]	[%]	[MW]	[%]	[MW]	[%]
C-1	Compressor	1.90	60.00	0.79	1.94	1.01	62.83	0.34	1.02
C-2	Compressor	0.11	26.77	0.34	0.83	0.08	30.78	0.11	0.31
C-3	Compressor	2.45	62.73	0.88	2.16	1.47	67.00	0.42	1.24
C-4	Compressor	2.06	62.58	0.77	1.90	1.39	66.97	0.39	1.17
C-5	Turbine	3.35	30.77	4.24	10.41	3.34	35.64	4.07	12.13
P-1	Pump	5.92	64.18	1.81	4.44	4.92	68.52	1.35	4.03
HX-1	HeatEx	4.56	70.38	1.44	3.53	4.63	76.13	1.27	3.79
HX-2	HeatEx	9.72	65.87	2.85	6.99	8.95	69.60	2.46	7.34
HX-3	HeatEx	3.82	67.46	1.24	3.03	3.57	72.65	0.98	2.93
HX-4	HeatEx	0.88	65.23	0.44	1.07	0.58	69.16	0.16	0.48
R-1	Combustor	–	–	–	–	–	–	–	–
V-1	Separator	4.73	66.63	1.52	3.72	2.67	71.70	0.75	2.24
G-1	Generator	0.00	0.00	0.69	1.68	0.00	0.00	0.69	2.07
M-1	Mixer	3.67	63.61	1.20	2.94	3.09	68.03	0.85	2.53
ASU	Air Sep.	1.43	35.06	1.72	4.23	0.19	33.78	0.25	0.73
CPU	CO2 Pur.	0.74	63.66	0.44	1.07	0.03	3.22	0.04	0.13
Overall Process		45.33	36.64	20.35	49.94	35.93	39.75	14.15	42.14

Discussion

- High efficiency of the cycle at reasonable component parameterizations
- Combustor, turbine, recuperator, and ASU have the highest exergy destruction
- Recycle section
- Combustor, turbine, and ASU have the highest endogenous exergy destruction
- Main option to improve cycle efficiency is combustor-turbine section
- Combustor technology is most important for cycle efficiency (strong interaction) – particularly the recycle section
- Exergetic efficiencies/exergy destruction ratios of the main cycle components are comparable to other oxy-combustion cycles

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
- Recycle inefficiencies are traced back to the combustor
- Potential for improvement has been identified; high importance: combustor-turbine section, recycle section
- Study is a starting point for more detailed studies considering CO_2 purification and compression, recycle design
- Future: thermoeconomic analyses of the cycle

Modeling Assumptions I

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

Modeling Assumptions II

Parameter		Base Case	Variation
HeatEx E-1, E-2, Temperature Difference	K	7.5	± 2.5
HeatEx E-1, E-2, Pressure Drop (gas)	%	2	± 0
HeatEx E-1, E-2, Pressure Drop (liquid)	%	4	± 0
HeatEx E-3, Pinch Temperature Difference	K	3	± 2
HeatEx 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_{O_2}	250	± 50
CO_2 Purification, Specific Power Demand	kWh/kg_{CO_2}	10	± 0

Site Conditions/Reference 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

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

Methane (CH_4)	0.931 mol/mol	Lower Heating Value (LHV)	47457 kJ/kg
Ethane (C_2H_6)	0.032 mol/mol	Higher Heating Value (HHV)	52581 kJ/kg
Propane (C_3H_8)	0.007 mol/mol	Temperature	38.0 °C
n-Butane (C_4H_{10})	0.004 mol/mol	Pressure	30 bar
Carbon Dioxide (CO_2)	0.010 mol/mol		
Nitrogen (N_2)	0.016 mol/mol		