Innovative Flue Gas-to-sCO_2 Primary Heat Exchanger Design for Cement Plant Waste Heat Recovery

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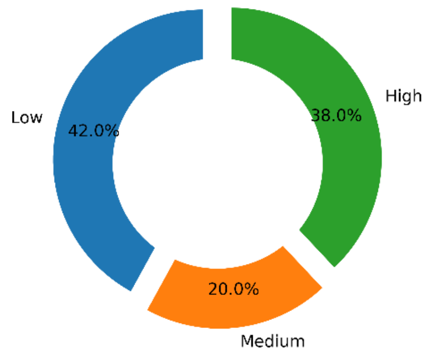
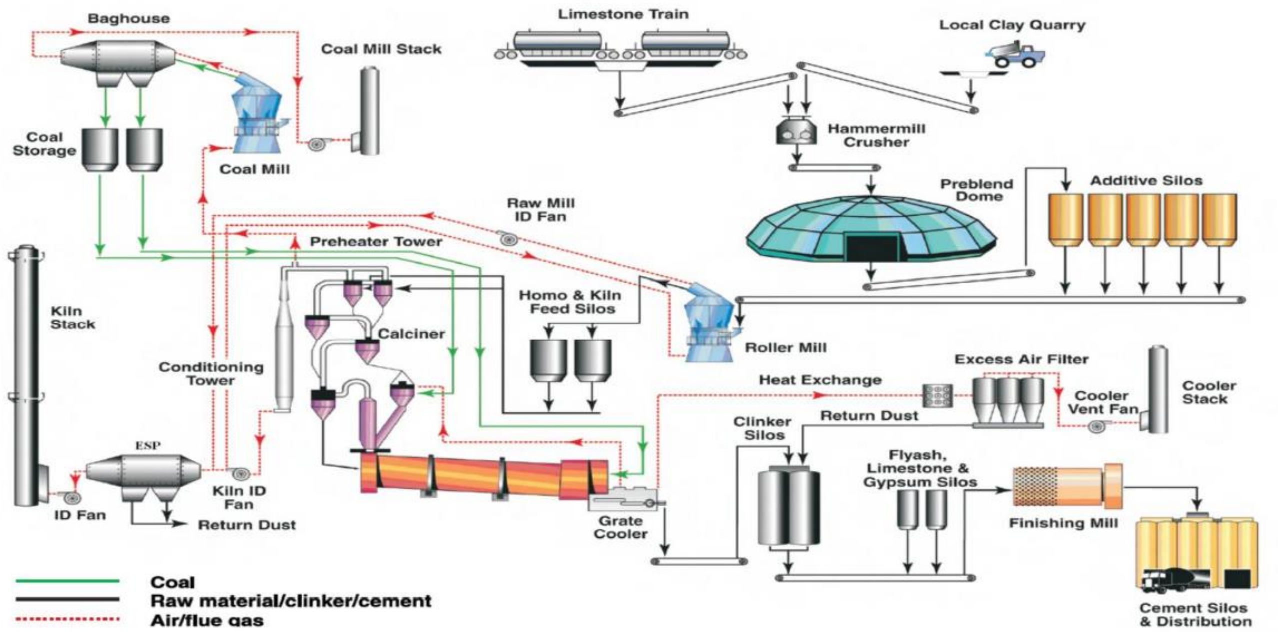
02/23/2022

The 7th International Supercritical CO_2 Power Cycles Symposium
February 21 – 24, 2022, San Antonio, Texas
Paper 181

Introduction – Cement Industry

- Cement production is an energy-intensive process.
- Cement production requires raw materials to be heated to 1400°C.
- Thermal energy only accounts for approximately 35% of the cement industry's CO_2 emissions.
- Based on GNR (Getting the Numbers Right) data for the year 2010, the European average thermal energy needed to produce a tone of clinker is 3,733 MJ.
- Exhaust gases from kiln operations can reach up to 600 °C. – Potential heat source for waste heat recovery systems
- Improving the energy efficiency of a cement plant will dramatically improve its bottom line.
  - Waste Heat Recovery systems are the key for transfer current cement plants to greening cement plants

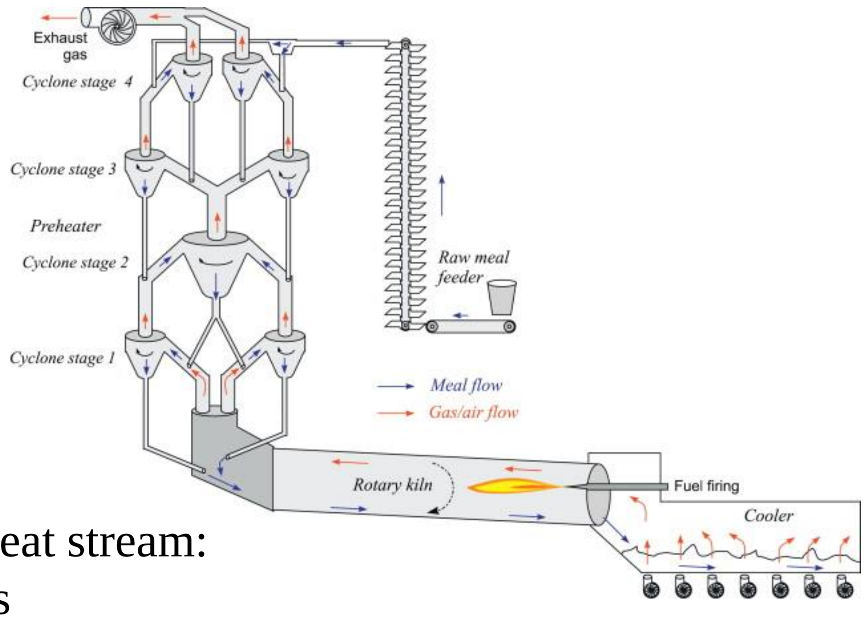




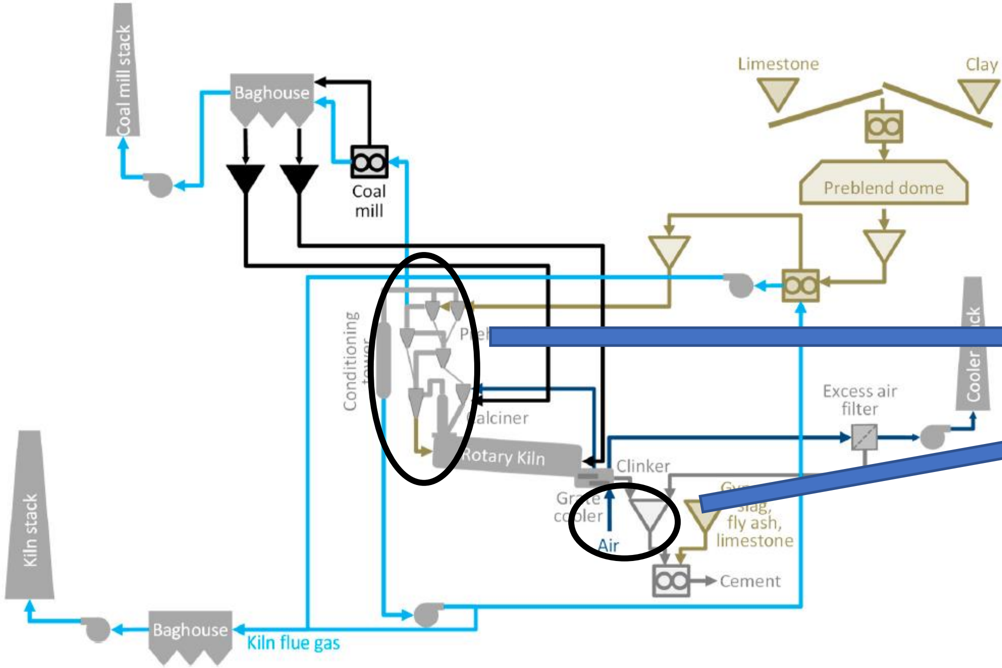
Cement Industry - Process description:

- Raw material is heated up to 1400 °C
  - Chemical reaction and melting process to fuse the clinker (product).
  - Raw material: Limestone, clay, fly ash, gypsum, and/or iron ore
- The heating takes place in the kiln - rotating cylinder vessel.
  - A fuel (typically coal) is burning in the kiln.

K. S. Stadler, J. Poland, and E. Gallestey, “Model predictive control of a rotary cement kiln,” Control Eng. Pract., vol. 19, no. 1, pp. 1–9, 2011, doi: https://doi.org/10.1016/j.conengprac.2010.08.004.



Two types of kiln:
- Wet
- Dry



Type of the waste heat stream:
- Exhaust gas
  - Preheater
  - Cooler (clinker)

The typical temperature range is between 300 and 450 °C
- In some cement plant can go up to 600 °C

M. G. Plaza, S. Martínez, and F. Rubiera, “CO2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations,” Energies, vol. 13, no. 21, 2020, doi: 10.3390/en13215692.

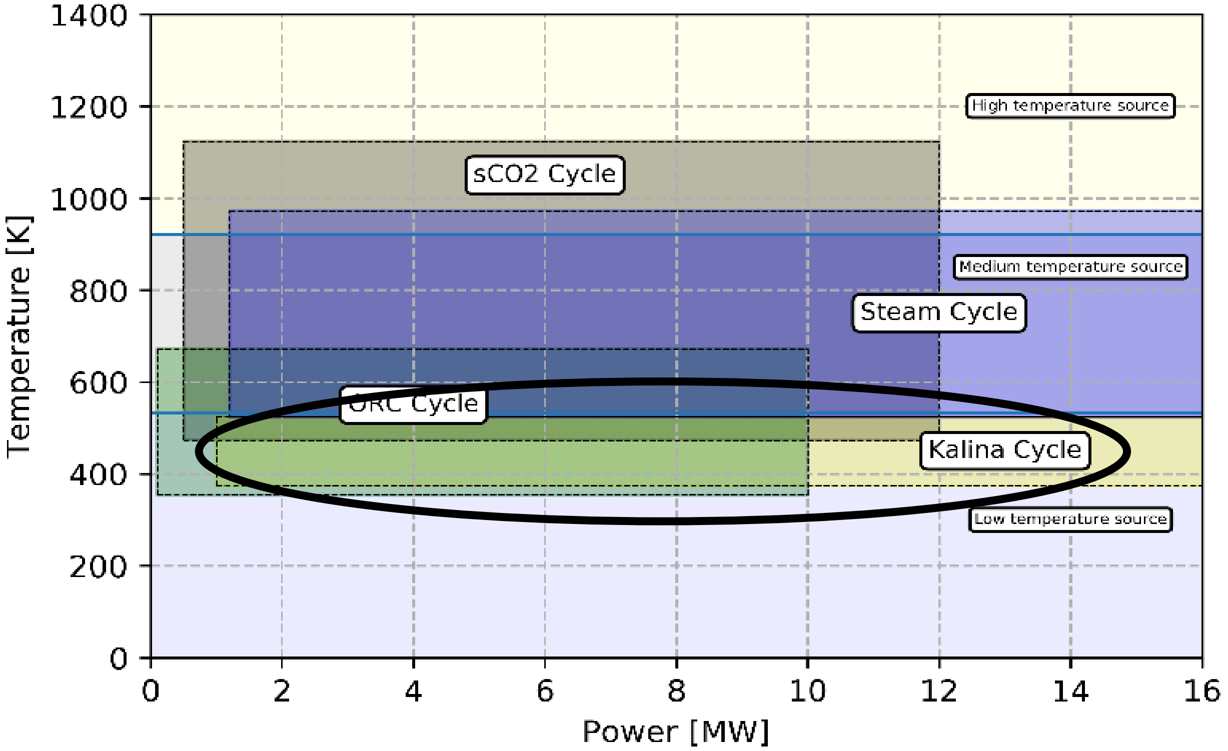
Cement Industry – Typical waste heat stream parameters

The typical production in in 2008 in the US is 80 % for dry kiln

	Average exhaust temperature	Production (2008) in US
	K	%
Wet kiln	611.15	20
Dry kiln:		80
No preheater/precalciner	722.15	18
Preheater	611.15	19
Precalciner	611.15	43

Proposed cycles for WHR:

- Organic Rankine cycle
- Steam cycle
- Kalina cycle
- sCO2 cycle



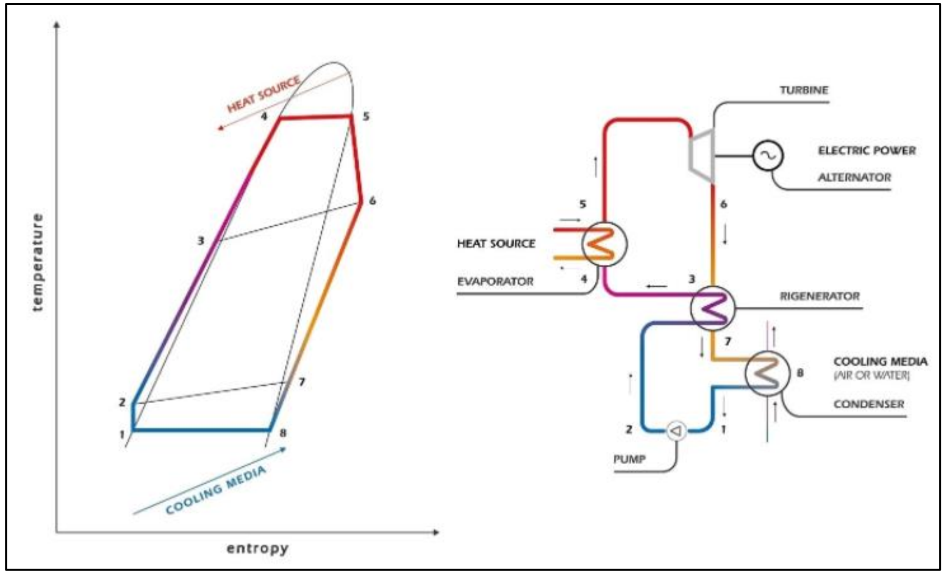
The composition of the exhaust gas:

- The typical substances are H_2, H_2O, CO_2, and O_2.

Industry	Process	Temperature	Current WHR system
Cement	Wet kiln	300 – 350 °C	ORC
	Dry kiln (without preheater or precalciner)	400 – 450 °C	ORC
	Dry kiln (recovered)	300 – 350 °C	ORC

Cement Industry – Organic Rankine cycle

- Organic Rankine Cycle plants have been deployed in the cement industry for 2 decades
- Leading equipment vendors include Turboden and ORMAT
- Heat sources: clinker coolers and preheaters
- Multiple commercial references in Europe, India, Turkey, MENA
- Power levels 1-8 MWe
- Advantages of ORC systems
  - Small sizes match heat source capacities
  - Unattended operation possible
- Disadvantages of ORC systems
  - Working fluids have thermal limits of ~300°C
  - Intermediate heat transfer loop required using thermal oil or pressurized water



4 MWe ORMAT ORC system at Ultratech Cement, India

5 MWe Turboden ORC system at CRH Slovakia

Cement Industry – Steam Rankine cycle

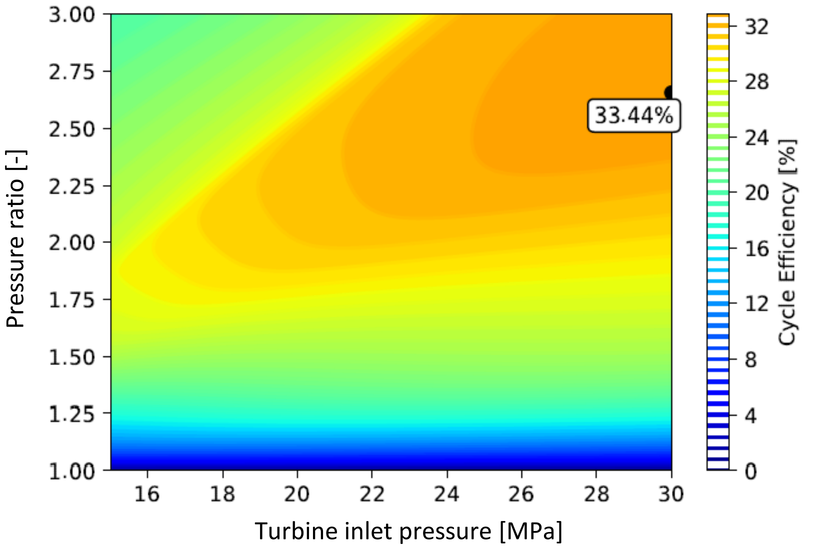
- Steam cycles leverage well demonstrated components and established supply chain
- Commercial plants denominated by China with hundreds of references and strong government support
- Advantages of steam Rankine systems
    - Well known technology
    - Thermally stable working fluid
- Disadvantages of Steam Rankine systems
    - Water treatment required
    - Specialized operators required
    - Freeze protection required

Kawasaki steam WHR references

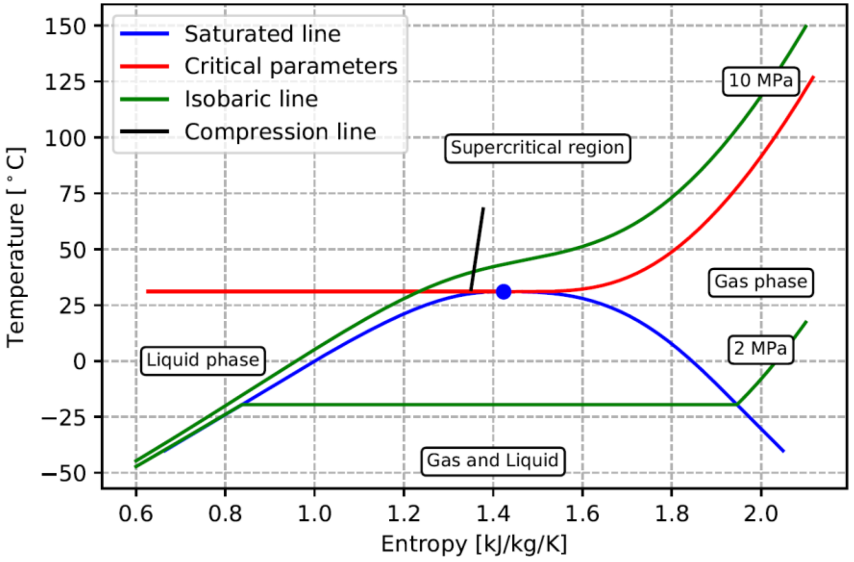
Cement Industry – sCO2 power cycle:

- The Supercritical CO_2 (sCO_2) power cycle is a relatively new concept with high efficiency.
- The main reason for the interest of the sCO_2 power cycle is its theoretical and practical promise of compactness, high efficiency, and wide-range-applicability.
- The sCO_2 power cycle can be used for majority of heat sources, which are used in energy conversion systems
- The main applications:
  - waste heat recovery systems
  - solar power plants
  - geothermal power plants
  - fossil power plants
  - nuclear power plants

Application	Power [MWe]	Operation Temperature [°C]	Operation Pressure [MPa]
Nuclear	10-300	350-700	20-35
Fossil fuel (syngas, natural gas, coal)	300-600	550-1500	15-35
Geothermal	10 - 50	100-300	15
Concentrating solar power	10 - 100	500 - 1000	35
Waste heat recovery	1 - 10	200 - 650	15- 35



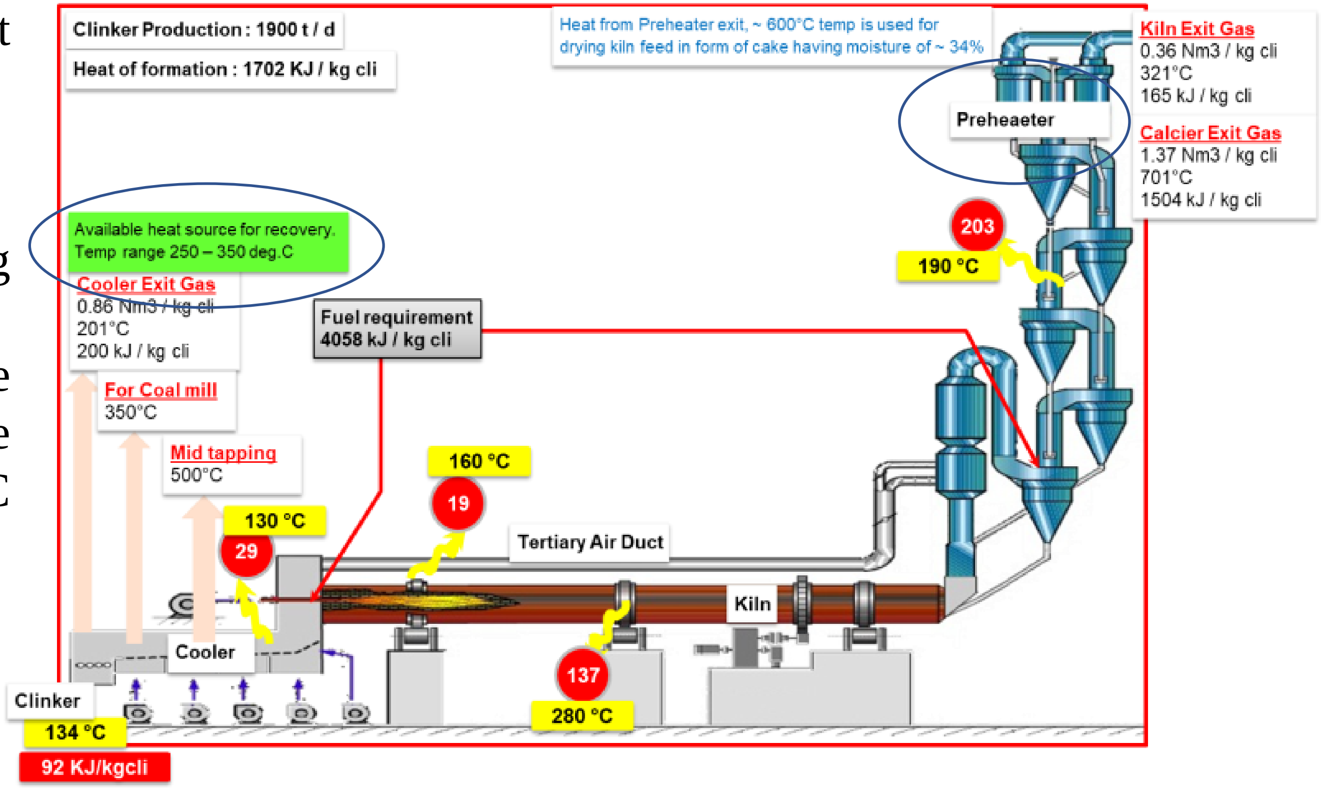
L. Vesely, "Study of power cycle with supercritical CO2," Dept. Energy Eng., Czech Tech. Univ. Prague, Prague, Czechia, Tech. Rep., 2018.

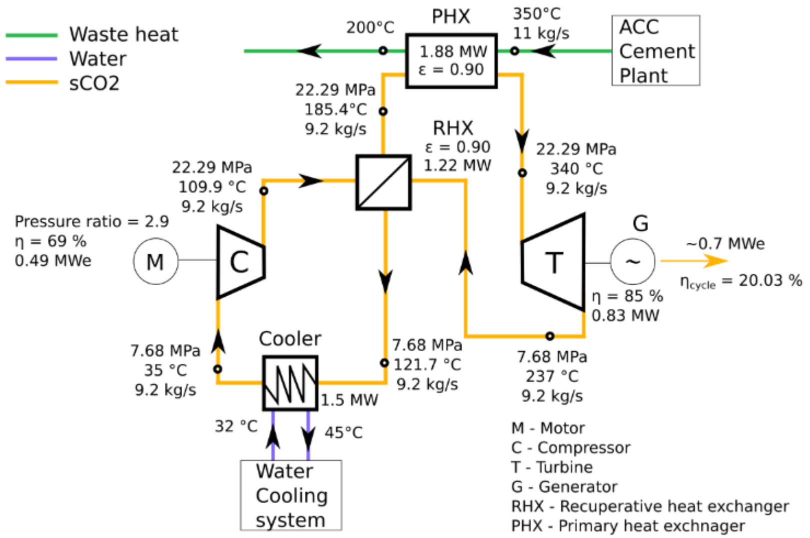


- <u>The waste heat recovery system considered for the current study is in the range of 1 to 10 MWe, with the operating temperature between 200 to 600 °C.</u>

Cement Industry – ACC Madukkarai plant Layout - Available Heat Potential:

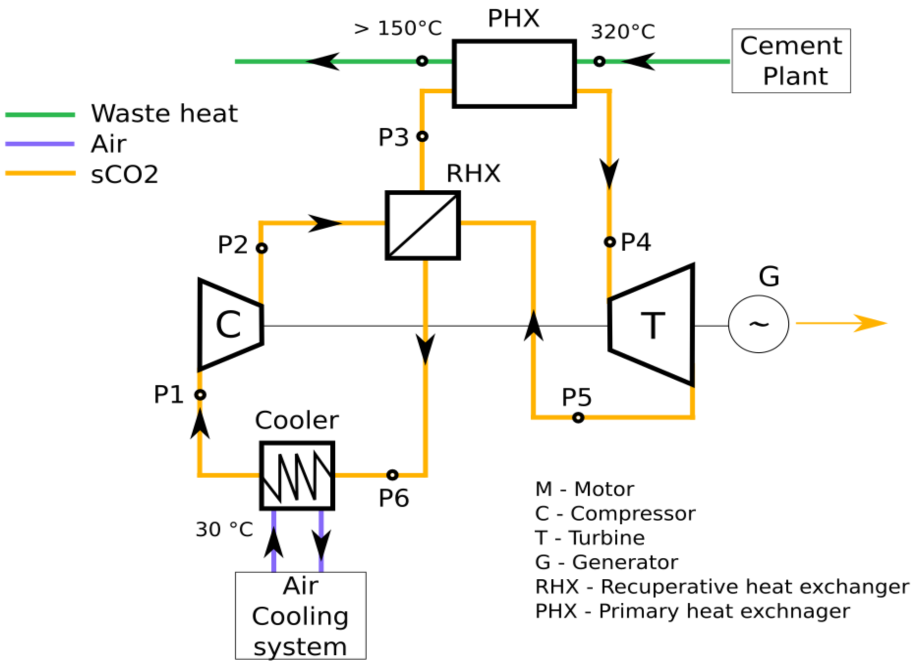
- The hot, dust-laden exhaust gases from the cement plant can be tapped from two sources
    a. Clinker cooler
    b. Preheater.
- Waste heat recovery can be operated at different heating levels range from 200 to 600 °C.
- The tertiary air duct and the cooler blowers can be managed for the hot air recovery of the plant and the temperature availability is varying from 500 °C to 201 °C at different tapping points.





Cooler exit gas	201	°C
Coal mill	250 - 350	
Preheater	600	

Cement Industry – sCO2 WHR unit - optimization:



Parameter	Lower	Upper	
Pressure ratio	2.5	3.5	-
Compressor outlet pressure	20	25	MPa
Turbine inlet temperature	300		°C
Compressor inlet temperature	32		
Turbine efficiency	85		%
Compressor efficiency	69		
Recuperator effectiveness	90		

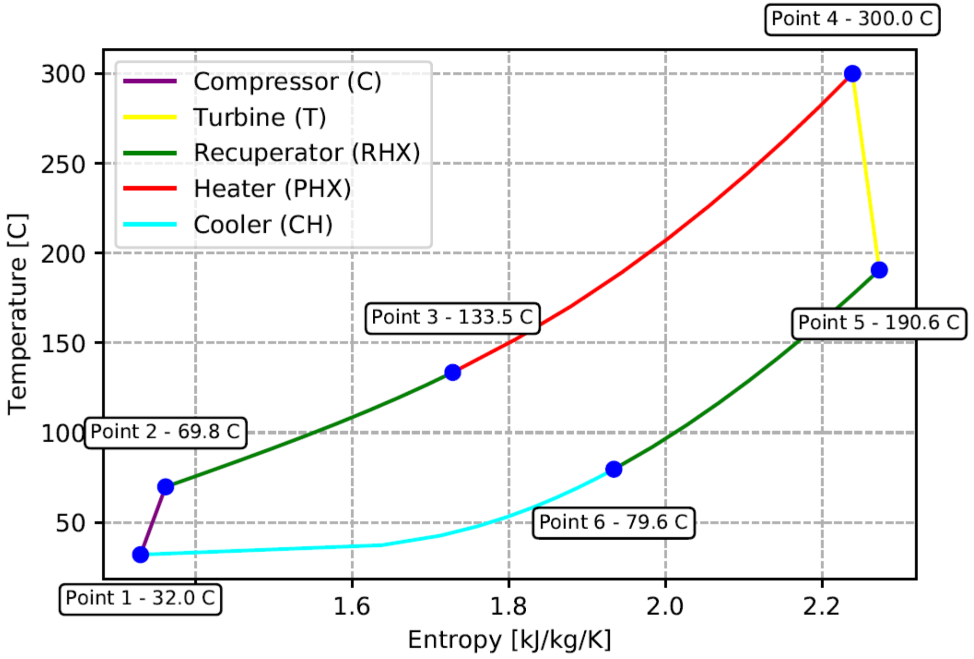
Composition of exhaust gas	Flow rate, kg/hr	% by weight
N_2	151,196	57.1
CO_2	100,319	37.9
O_2	10,092	3.8
H_2O	2,367	0.89
H_2	740	0.28
SO_2	25	0.01

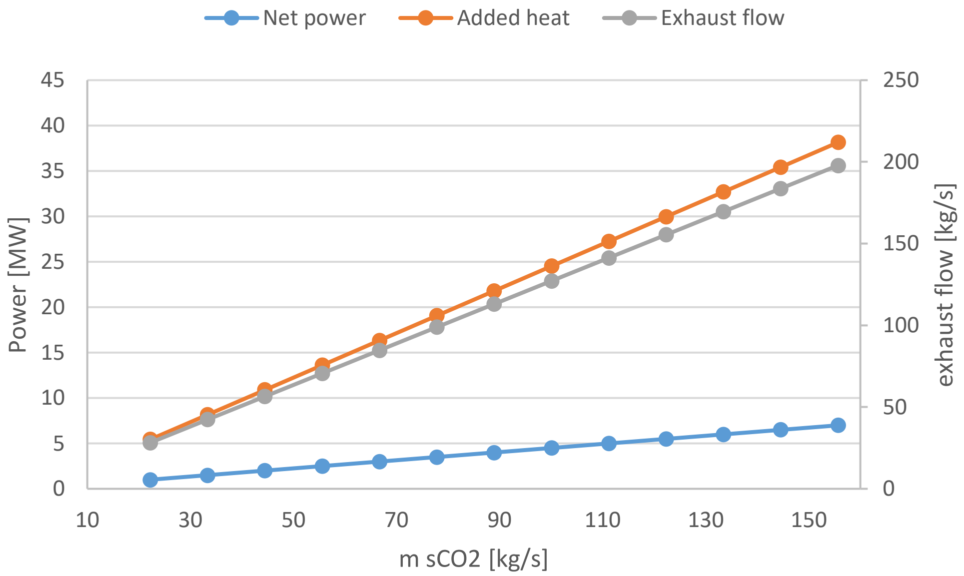
Basic data & Assumptions for the Calculation:

- Kiln capacity: 3000 tonnes per day
- No of stages in the preheater: 5
- Preheater exit gas details
  - Volume: 1.5 Nm^3 / kg clinker
  - Specific heat capacity: 0.36 kCal / kg / °C
  - Temperature: 316 °C
- Cooler exit gas details
  - Volume: 1.0 Nm^3 /kg clinker
  - Specific heat capacity: 0.317 kCal / kg / °C
  - Temperature: 300 °C

The generator efficiency is 96 %, clutch efficiency is 95 % and gearbox efficiency is 93 %. efficiency and therefore will reduce net power

Cement Industry – sCO2 WHR unit – optimization results:

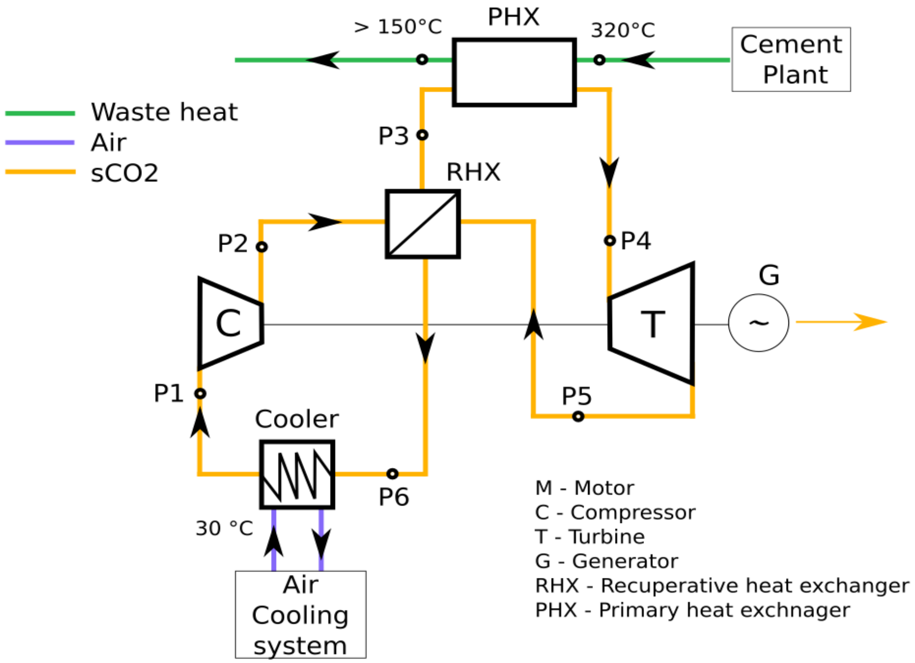




Cycle efficiency	21.82							%
Turbine power output	1.98	3.96	5.94	7.92	9.90	11.88	13.86	MWth
Compressor input power	0.78	1.56	2.34	3.11	3.89	4.67	5.45	
Added heat	5.45	10.90	16.35	21.80	27.25	32.70	38.15	
Removed heat	4.27	8.54	12.81	17.08	21.36	25.63	29.90	
Regenerative heat	3.05	6.10	9.14	12.19	15.24	18.29	21.33	
Net power	1.00	2.00	3.00	4.00	5.00	6.00	7.00	MWe
Flow rate sCO_2	22.3	44.5	66.7	88.9	111.2	133.5	155.7	kg/s

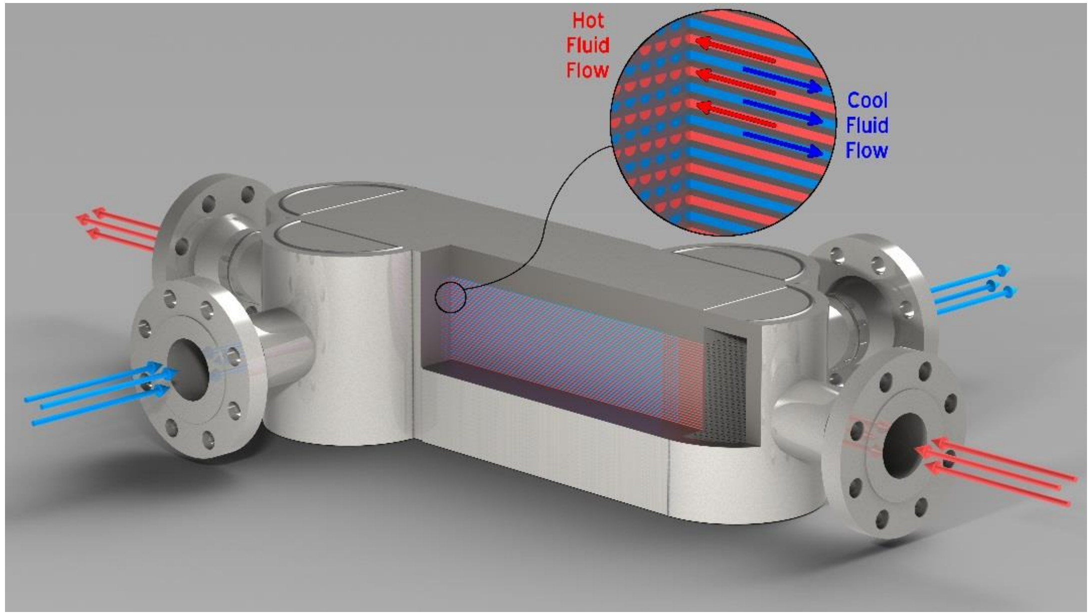
Cement Industry – sCO_2 heat exchangers design:

- sCO_2 cycles are highly recuperative cycles in which the cycle efficiency is directly linked to the effectiveness for the various heat exchangers in the loop.
- Various heat exchanger designs and technologies can be used for sCO_2 cycles such as tubular or plate based heat exchangers.
- High temperature and pressure nature of the system requires heat exchangers with high mechanical integrity.
- Printed Circuit type Heat Exchangers (PCHEs) are predominantly used as high and low temperature recuperators as well as water-CO_2 coolers, due to their high effectiveness and mechanical performance.
- Tubular type heat exchangers used as primary heat exchanger in a form of finned tube coil bundles as well as dry coolers as fin-fan coolers when water is not used as coolant.
- Recently, Vacuum Process Engineering, Inc. introduced a hybrid PCHE/Fin designs for primary heat exchanger and dry coolers



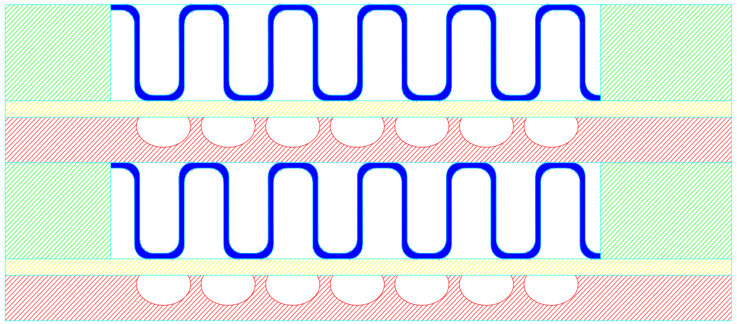
Cement Industry – sCO2 heat exchangers design:

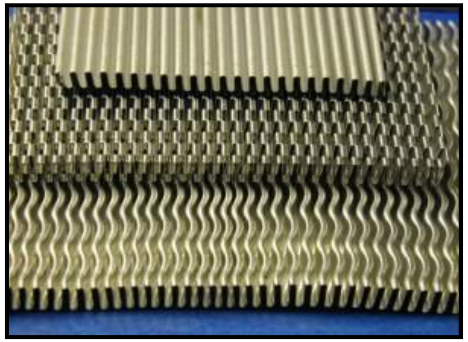
- In PCHE designs, fluid flow paths designed using proprietary algorithms with nearly unlimited layout (only limitation of being able to draw within a 2-D space) are formed by either photo chemical etching or other methods.
- Specific channel layouts dedicated for hot and cold stream respectively are then stacked (hot-cold-hot-cold….)



Courtesy of VPE, Inc.

- Hybrid Plate Heat Exchanger as PHEs use chemically etched microchannel plates for the high pressure working fluid and formed fins of various geometry for the low pressure exhaust gas stream

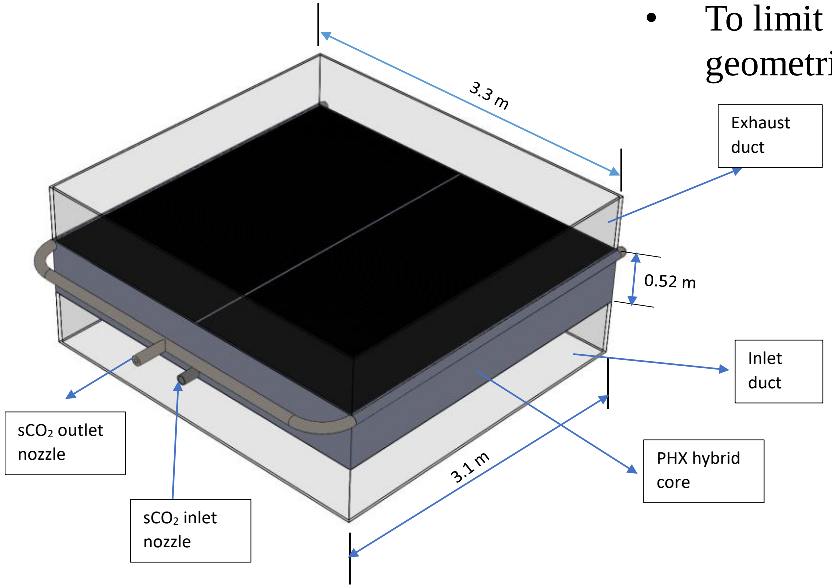




Courtesy of VPE, Inc.

Cement Industry – sCO2 primary heat exchanger design:

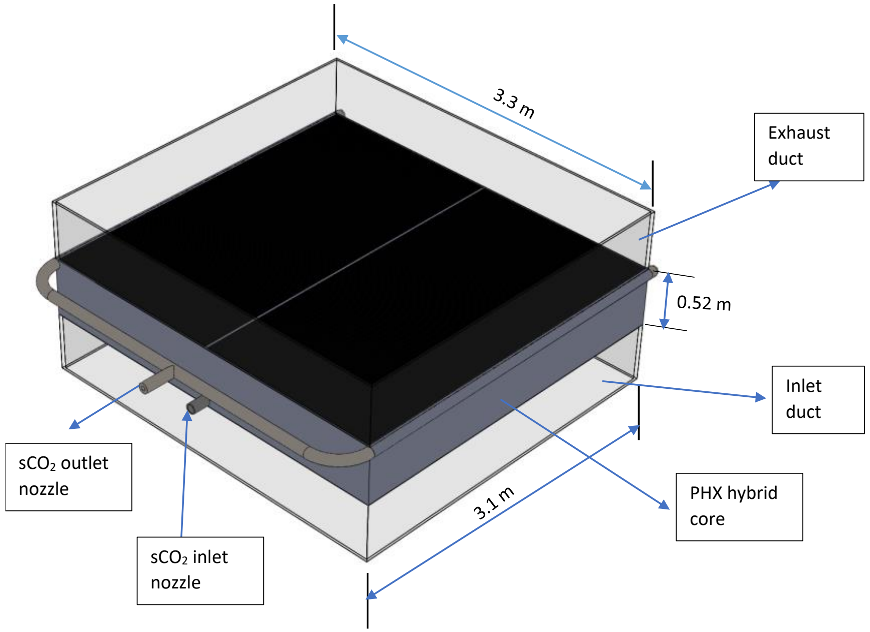
- The design layout for the single module is optimized for lower footprint, low material uses, and ease of installation or transport packaging.
  - stainless 300 series are considered for material of construction.
    - Supercritical CO2 recuperators and coolers predominantly used **SS316**, although there is limited long-term use material property data
      - SS310 with higher resistance to oxidation, SS304 (economical alternative), and SS347.
- PHX design is estimated to weigh 22 tons
- The PHX design for the 10.9 MW thermal module.
  - It uses a once-through exhaust gas stream flowing upwards or sideways through the heat exchanger core from an exhaust duct.
  - The exit from the heat exchanger core passes through a stack and is released to the ambient atmosphere.
  - To limit back pressure, the exhaust stream flow length is shortened, while heat transfer is enhanced using featured fin geometries.



		Exhaust		sCO_2	
	Unit	In	Out	In	Out
Flow rate	kg/sec	58.3		44.5	
Temperature	^0C	320	148	133.5	300
Inlet Pressure	Bar	1.05		245	
Pressure drop	kPa	3		460	
Thermal Duty	MW	10.9			

Cement Industry – sCO2 primary heat exchanger design:

- The pressure drop for the cooler is assumed ad hoc to be 1.5 % of the low-pressure side pressure, and the pressure drops for the RHX are considered to be 2 % of the low/high-pressure side pressure.
- When these pressure drops are included, the net power output drops to 1.84 MW for sCO_2 flow rate of 44.5 kg/s. The sCO_2 mass flow rate, and hence also the PHX pressure drop, are adjusted until the net power output is computed to be 2.00 MW.



	No dP	With dP	With dP + optimization at 2 MWe	
Cycle efficiency	21.82	20.33	20.3	%
Pressure drops				
PHX	0	460	498	kPa
RHX – low pressure side	0	156	156	
PHX – high pressure side	0	500	500	
Air Cooler	0	117	117	
Cycle results				
Turbine power output	3.96	3.73	4.03	MW
Compressor input power	1.56	1.56	1.69	
Added heat	10.90	10.66	11.53	
Removed heat	8.54	8.49	9.19	
Regenerative heat	6.10	6.39	6.92	
Net power	2.00	1.84	2.0	MWe
Flow rate sCO_2	44.5	44.5	48.1	kg/s

Thank you for attention