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Innovative Flue Gas-to-sCO$_2$ Primary Heat Exchanger Design for Cement Plant Waste Heat Recovery

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ABSTRACT

Waste heat is a net-zero emissions energy source found in many industrial processes such as in gas turbine exhaust gas as well as in chemical, steel, incineration, glass, and cement industries. Many such heat sources are above the upper temperature limit for conversion to power using traditional Organic Rankine Cycle (> 300 °C). In this paper, we have investigated use of the sCO$_2$ cycle to meet some of the in-house power requirements of a cement plant by recovering waste heat from the plant's flue gas that typically exits at 400 °C. In large plants it is estimated that up to 7 MWe may be recoverable. A sCO$_2$ based power conversion approach could exploit the compactness of the sCO$_2$ turbomachinery for retrofit applications as well as in new plants. From a total system perspective, however, the flue gas-to-sCO$_2$ primary heat exchanger (PHX) must also be compact and effective at these temperatures while being compatible with the aggressive nature of the flue gas that includes susceptibility to corrosion and to dust particle loading up to 100g/Nm^3 contributing to erosion. Typical mass flow rate of exhaust gas is around 485 tons/hour with a composition that includes CO_2 (14-33% (w/w), NO_2 (5-10% of NOx), NOx (<200-3000 mg/Nm^3), SO_2 (<10-3500 mg/Nm^3) and O_2 (8-14% (v/v). Based on optimization techniques used in Printed Circuit Heat Exchanger (PCHE) design and manufacturing, this paper describes a microchannel design suitable for the flue gas-to-sCO$_2$ PHX that also considers parasitic losses and an appropriate approach temperature. Detailed PHX-level and system level techno-economic evaluations are recommended along with performance and environmental benefits, to establish the viability of the sCO$_2$-based waste heat recovery system in cement and other applicable industries.

INTRODUCTION

Emissions of carbon dioxide (CO_2), a greenhouse gas (GHG) pollutant from thermally intensive manufacturing processes (e.g., cement, steel, and glass) arise from use of fossil fuel (typically coal and metallurgical coke produced from coal) for the required high-temperature heat (e.g., up to 1650 °C in cement kiln operations). Additional CO_2 emissions also arise from use of fossil fuel to generate secure and reliable electric power for the plant's operations from within the plant boundary. With respect to cement, reduction of the CO_2 emissions to achieve "green" production would therefore require multiple approaches to provide the required heat. One approach, for example, envisions replacing heat with combustion of green hydrogen instead of coal to reduce/eliminate the associated emissions, although such a principle remains to be tested [1]. Emissions reduction may be also achieved through use of renewables for the in-house power, but these would either require storage or supplementary fossil fuel use because of their intermittent availability.

Options exist for improving efficiency (and thus to further reduce emissions) in cement plants by recovering the relatively high-temperature enthalpy from the waste heat arising from kiln operations if such enthalpy is converted to power [2]. Flue gas from kiln operations such as preheaters and clinker coolers can reach up to 450 °C [3]. Supercritical carbon dioxide (sCO_2) power conversion cycles may offer an improved efficiency over other power cycles such as organic Rankine or steam Rankine cycle [4], [5]. Given the compactness of the sCO_2 turbomachinery, the equipment may also be retrofitted in existing plants [6]. Ref. [7], [8] provide clear, worldwide examples and the extent to which use may be made of such waste heat. According to the same references, these plants currently operate with traditional steam Rankine cycle or organic Rankine cycle (ORC) power conversion technologies. While subsequent literature mentions the potential attractiveness of the sCO_2 power conversion for the cement industry [2], a detailed examination of its implementation is now possible in view of the maturing of this power conversion technology.

In a recent paper [9], a case study was presented for retrofitting sCO_2 power conversion equipment in an existing cement plant. The plant, located in Tamil Nadu state in India, has already pioneered using renewable power to offset some coal use, and uses Municipal Solid Waste (MSW) to augment caloric needs of the kiln. Results of the study support deploying a low-temperature, smaller scale demo to obtain scale-up data and techno-economics. Additional use of MSW may lead to design and operating conditions with lower CO_2 emissions, replacement of the existing (second) coal boiler and a desired pay-back period for the operator while lowering the landfill burden to neighboring communities, all leading to further "greening" cement production. During the course of this study, the need for a compact primary heat exchanger (PHX) for the cost-effective transfer of the flue gas waste heat to sCO_2 was identified as unique component. In this paper, we examine the characteristics of the flue gas and an optimized and practical design for this equipment. While recovering up to 7 MWe of power is practical as further described below, this paper focuses on the demo scale system producing 2 MWe.

CEMENT PLANT DESCRIPTION

The main part of the cement production process consists of a rotary kiln, a clinker cooler, and a preheater. A significant amount of heat is carried by preheater exhaust gas and cooler exit air. The clinker (final product) is cooled in the clinker cooler by a gas/air flow. The gas/air stream continue via the rotary kiln to the preheater, see Figure 1. The preheat is used to dry raw material.

The cement plant can be operated with wet or dry kiln. The dry kiln is designed with or without preheater and pre-calciner [10]. The typical production of the clinker in 2008 in the United States was 20 % wet kiln and 80 % dry kiln. Depending on the number of stages in the pre-heater and the type and technology adopted in the cooler section the temperature in these gas streams ranges from 200 °C to 360 °C /450 °C [2], [3], [10]–[13], see Table 1. The typical waste heat recovery system for cement plant application is the organic Rankine cycle (ORC) [13]. However, in some cement plants, steam Rankine cycle is also used [14].

Table 1.: Available waste heat for Cement plant [13]

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

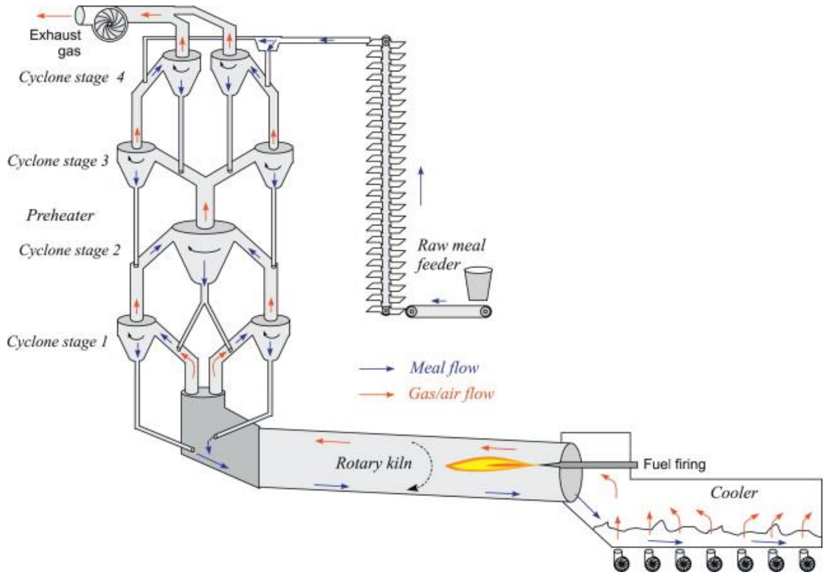

Figure 1.: Schematic of rotary kiln for the cement plant [15].

If the moisture content in the raw material such as limestone and/or fly ash is high, this heat is utilized effectively to remove the moisture present in these materials. Otherwise, the heat is rejected to the atmosphere, and therefore there is a potential to recover it. Options exist for improving efficiency (and thus to further reduce emissions) in cement plants by recovering the relatively high-temperature enthalpy from the waste heat arising from kiln operations if such enthalpy is converted to power. Exhaust gases from kiln operations can reach up to 450 °C [2], [3], [10]–[12] (for a specific cement plant it can reach up to 600 °C [9]), see Figure 2.

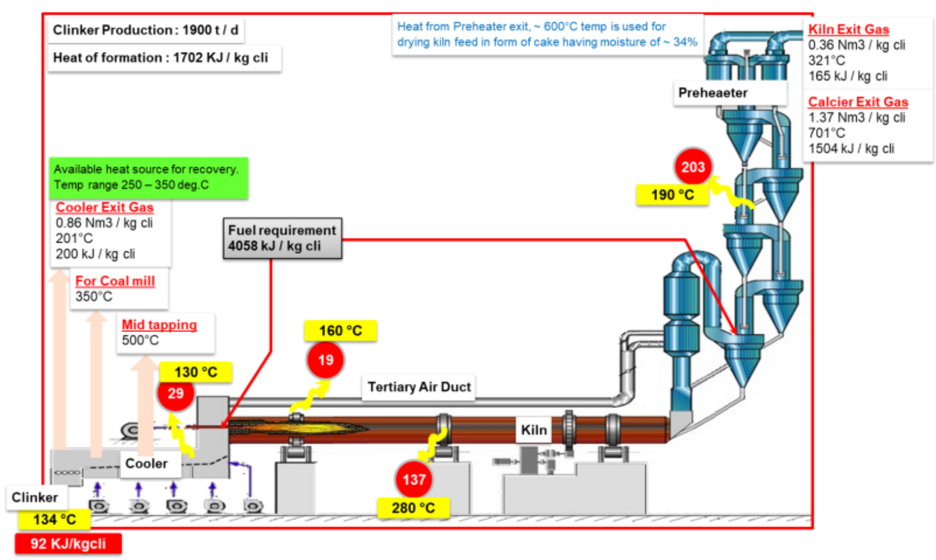

Figure 2.: Cement plant block flow diagram (ACC Madukkarai plant, India) [9].

The heat availability in an individual kiln/cooler may be less, the total heat availability in the location including all the kilns may add up to a sizable waste heat recovery potential. The presence of dust in the primary heat exchanger can reduce the heat transfer rate by producing a coating over the heat transfer zones, lowering the cycle's efficiency. The presence of dust can cause abrasion, resulting in the failure of tubes and heat transfer equipment.

Composition and Parameters of the Waste Heat

The cement plant has typically two sources of waste heat in the kiln exhaust gas (arising from the high temperature de-carbonation of limestone and the combustion). The CO_2 concentration in the flue gas is quite high relative to other industrial exhaust gas streams. The exhaust gas stream from the separator contains CO_2, N_2 and excess O_2 which are shown in Table 2. The percentages of N_2 and CO_2 are 57.1% and 37.9% respectively [16]. The flue gases from cement plant must also follow local pollution abatement standards. The basic data & assumptions for the calculation are shown in Table 3.

Table 2.: Composition of exhaust gas. [16]

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

Table 3: Basic data & Assumptions for the Calculation [16].

Kiln capacity	3000	tonnes per day
Number of stages in the preheater	5	
Preheater exit gas details		
Volume	1.5	Nm3 / kg clinker
Specific heat capacity	0.36	kCal / kg / °C
Temperature	316	°C
Cooler exit gas details		
Volume	1.0	Nm3 / kg clinker
Specific heat capacity	0.317	kCal / kg / °C
Temperature	300	°C

Current Approach (Benefits and Limitations)

As noted earlier, current approaches for waste heat recovery from cement plant flue gas utilize either ORC, or steam Rankine cycle power generation systems. There are multiple commercial references for ORC-based waste heat recovery systems at cement plants, mainly in Europe [8]. These systems are designed to accommodate the approximately 300 °C upper temperature limit of organic working fluids such as hydrocarbons and siloxanes [17]. Systems typically incorporate an intermediate heat exchange loop to transfer heat from the flue gas to either thermal oil or pressurized water which in turn heats the ORC working fluid in an external heat exchanger. This heat exchange loop adds additional CAPEX to the system while increasing the effective approach temperature, thereby lowering cycle performance. Typical primary heat exchangers (PHXs) resemble heat exchanger coils found in waste heat recovery units (WHRUs) or once-through steam generators (OTSGs). These are characterized by piping/tubing arranged in crossflow configurations, with the option of including fins to enhance the heat exchange surface area.

The cost and performance of cement plant waste heat recovery systems can be improved by increasing the compactness of the PHXs (as expressed by MWth/m^3 or MWth/ton) while designing them for direct exchange with a thermally stable working fluid such as sCO_2.

WASTE HEAT RECOVERY SYSTEM

The sCO_2 power conversion cycle may offer an improved efficiency compare to organic Rankine or steam Rankine cycle. Given the compactness of the sCO_2 turbomachinery, the equipment may also be retrofitted in existing plants [9].

The design of the sCO_2 waste heat recovery system for the cement plant application is the simple Brayton cycle layout, which consists of a primary heat exchanger (PHX), Cooler (water or air, according to localization and cooling availability), recuperative heat exchanger (RHX), compressor (C) and turbine (T), as shown in Figure 3. The boundary conditions are shown in Table 4. The exhaust inlet temperature is 320 °C and the outlet temperature must be equal or higher than 150 °C to maintain minimum temperature difference in the PHX as a design factor.

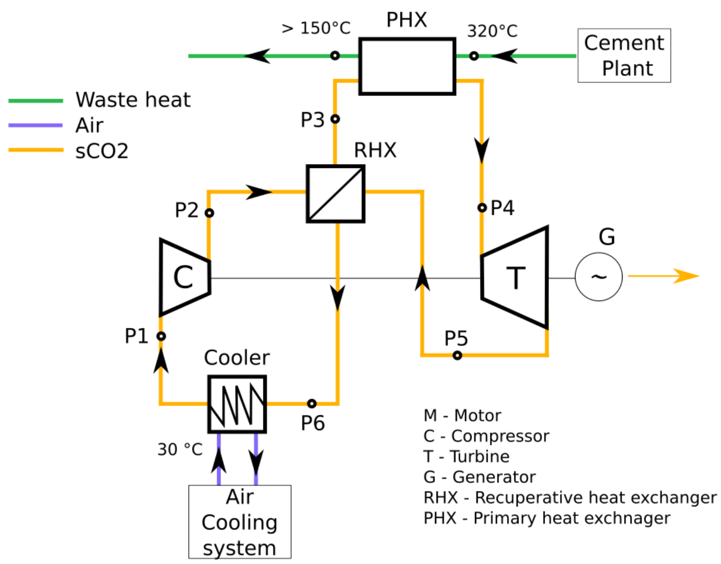

Figure 3.: sCO_2 block flow diagram of the WHR unit.

Table 4.: Boundary parameters.

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		

The generator efficiency is 96 %, clutch efficiency is 95 % and gearbox efficiency is 93 %, based on these the overall efficiency and the net power will be reduced. The pressure drops are not considered in the first calculation for all cases. However, the difference between the values will not be large (because, the maximal pressure drops will be between 1 - 2 %) [18], according to pressure drops calculated from detail design of the heat exchangers, which is second part of the cycle analysis.

PRIMARY HEAT EXCHANGER

A low cost and compact primary heat exchanger (PHX) that meets performance requirements both in terms of mechanical stresses and material compatibility of the exhaust stream is critical to the feasibility of WHR units for cement industries. There are limited options for primary heat exchanger in the market, that can handle high pressure working fluid such as supercritical CO_2 and compact. Conventional the state of the art tubular finned coils tends to require thick-walled tubes for the working fluid. Consequently, these would result in high thermal conductive resistance needing large surface area, as well as affecting their ability to handle thermal stress due to their high rigidity and non-uniform metal temperature distribution.

In this paper, a compact primary hybrid heat exchanger that uses chemically etched small channels for the sCO_2 stream (like sCO_2 PCHEs) and formed fins for the exhaust stream (like those used in plate fin heat exchangers) is proposed. The size of a waste heat recovery unit is primarily governed by the heat transfer coefficient of the exhaust stream side in relation to the working fluid side. Therefore, an optimization tool is used to reduce the size and material use of PHXs by utilizing better heat transfer channel geometry for the exhaust stream, while minimizing the pressure loss (reducing parasitic losses). Various formed fin types and form factors were evaluated based on a ratio of heat transfer enhancement factor (also called J-Colburn factor) and friction factor f (j/f). This performance parameter is also linked with cycle outputs.

Considering modularity aspect of the waste heat recovery unit for packaging and economical deployment, performance process conditions were also selected. To define the process conditions within the available heat source, various sCO_2 side parameters were compared using effectiveness of the PHX versus size of a single module. Once the preliminary cycle and system calculations were completed, the PHX design was performed to obtain sCO_2 pressure drop across the PHX for a nominal net power output of 2 MWe. The PHX is designed as modular heat exchanger to obtain all potential waste heat based on the required generated electrical power. However, this PHX pressure drop would affect the sCO_2 cycle performance. Hence, the sCO_2 cycle and system calculations were iterated upon with consideration of sCO_2 pressure drop in the designed PHX, and a design for 2 MWe net power was achieved. The size and manufacturing of the PHX were taken into the account in the design.

RESULTS

The cycle analysis was done for seven different cases and the simple Brayton cycle layout, as mentioned in Figure 3. Each case has a different added heat (PHX power) to the sCO_2 power cycle. The difference in added heat between the cases is approximately 5 MW. The T-s diagram for the Simple Brayton cycle is shown in Figure 4.

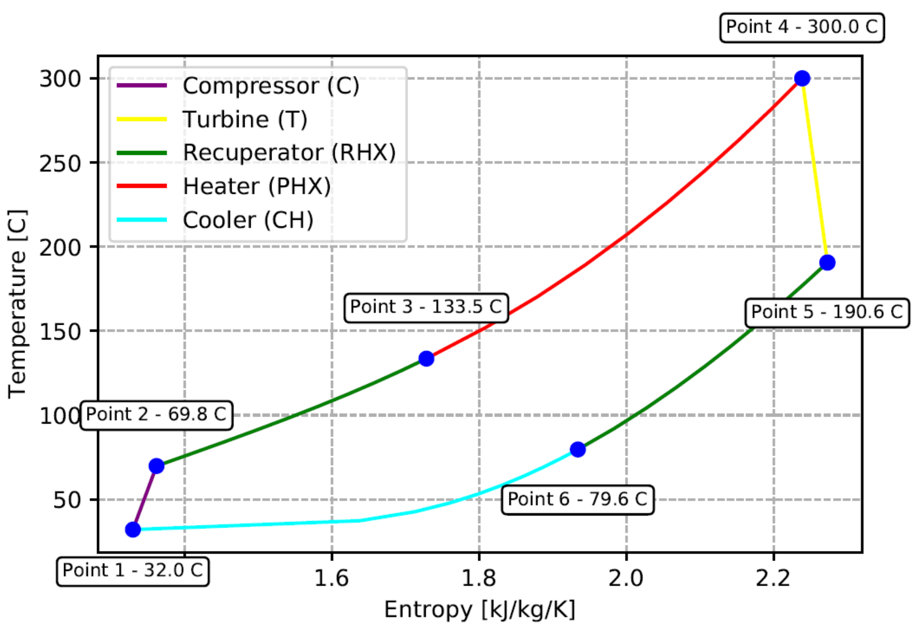

Figure 4.: T-S diagram of the sCO_2 WHR unit.

The resulting parameters of the sCO_2 WHR unit are shown in Table 5. The turbine inlet pressure is 25 MPa and the pressure ratio is 3.2. Figure 5 shows the sCO_2 and the exhaust mass flow and the added heat. The minimum exhaust gas temperature is 150 °C. The mass flow of the exhaust gas is defined by the supply compressors (gas/air flow) in the clinker cooler, see Figure 1. The results mentioned in Table 5 and Figure 5 are for sCO_2 power cycle without pressure drops. The cycle was optimized for 7 MWe net power.

Table 5.: sCO_2 power cycle WHR unit operation parameters.

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

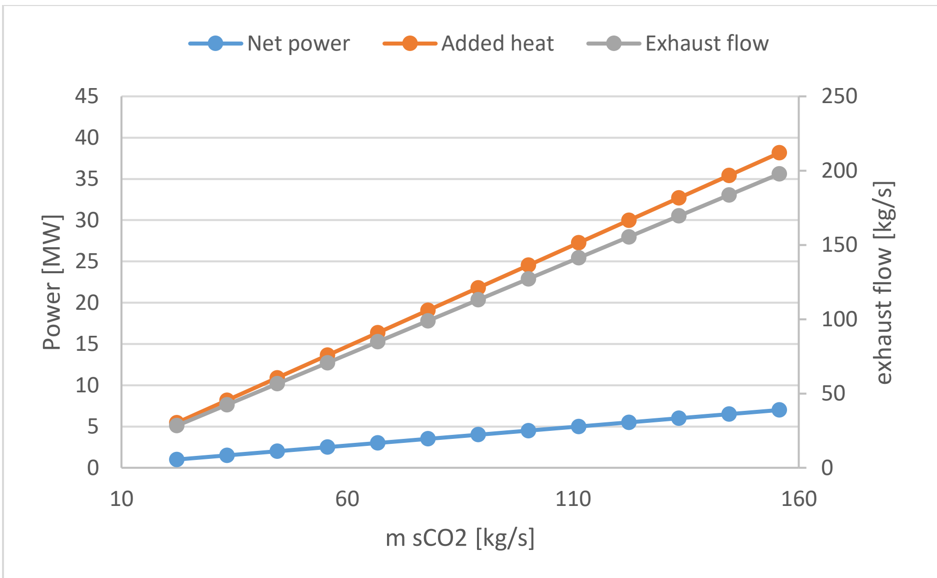

Figure 5.: sCO2 and exhaust flow rate for waste heat outlet temperature 150 °C.

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. Based on the exhaust stream compositions and maximum temperature, stainless 300 series are considered for material of construction. Supercritical CO_2 recuperators and coolers predominantly used SS316, although there is limited long term use material property data. Other grades such as SS310 with higher resistance to oxidation, especially for the exhaust stream, SS304 (economical alternative) and SS347 can all be alternatives to SS316. Diffusion bonding has another limitation in what kind of material are suitable for grain growth and bonding strength that is equivalent to parent metal. Chemical etching is also material composition dependent. However, the domestic (USA) companies that perform diffusion bonding have tested diffusion bonding and chemical etching of the above materials (SS316, SS310, SS304 and SS347) and developed a qualified process for diffusion bonding and chemical etching. Therefore, any of these materials are suitable for constructing the hybrid compact primary heat exchangers. For this study, SS316 was selected.

The PHX design for the 10.9 MW thermal module is shown in Figure 6. 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 pass through a stack and released to atmosphere. To limit back pressure, the exhaust stream flow length is shortened, while heat transfer is enhanced using featured fin geometries.

The above compact PHX design is estimated to weigh 22 tons. In comparison, a conventional design that used fin tube coils mass was estimated using an assumption that the area of the PHX is proportional to thermal duty/LMTD (Logarithmic Mean Temperature Difference). Based on conventional design information used for the Supercritical Transformational Electric Pilot (STEP) facility, which weighs 36 tons, but with a higher LMTD (109 °C) than the above PHX design for cement plants (18 °C LMTD), the weight estimate of the new design using conventional heat exchanger technology would have been roughly 100 tons. This is more than 4 times heavier. Given the current coil footprint for the STEP facility is also 7 m x 3 m x 4 m, a 100 ton versus 36 ton would also result in much bigger foot print than 7 m x 3 m x 4 m, while the above compact hybrid design has a foot print of 3.1 m x 3.3 m x 0.52 m (high). A significant improvement both in mass and footprint would result in lowering the capital and installation cost, while introducing easily packageable WHR power units.

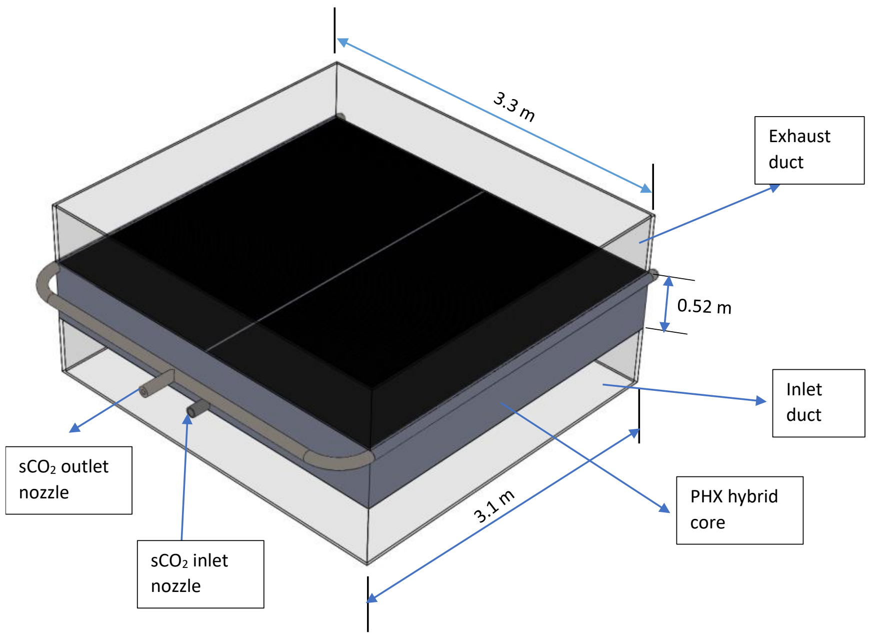

Figure 6.: Primary heat exchanger design layout.

Based on this PHX design, sCO_2-side pressure drop is calculated for the preliminary sCO_2 mass flow rate of 44.5 kg/s, which provided a nominal 2 MW net power output without any pressure drop as presented in Table 5 and Figure 5. Table 6 presents the computed pressure drops of a single PHX module for the selected operating conditions.

Table 6.: PHX inlet and boundary conditions.

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

As presented in Table 6, the pressure drop for the PHX is 460 kPa on the sCO_2 side, which affects sCO_2 cycle and hence the sCO_2 cycle and system is recalculated. No specific designs for the cooler or RHX are performed here, which are also required for recalculation of the cycle performance. Based on prior estimates of these pressure drops [18], here 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. The final results are shown in Table 7.

Table 7.: sCO_2 power cycle WHR unit operation parameters, with and without pressure drops

	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

*Note: dP – pressure drops

SUMMARY, CONCLUSIONS & RECOMMENDATIONS

This paper has focused on waste heat recovery from cement plants using Brayton cycle based on supercritical carbon dioxide (sCO_2) as the working fluid. Various waste heat parameters, such as flow rates, compositions, temperatures, other relevant flue gas conditions were collected. Operational parameters of a complete sCO_2 cycle were then computed through optimization based on those waste heat parameters, with the objective of presenting a design where a demo scale net power of 2 MW can be recovered from the waste heat stream.

An important and unique part of this sCO_2 system is the primary heat exchanger (PHX) that interfaces between the waste stream and the sCO_2 flow. An innovative design for this PHX was presented and flow calculations led to estimation of pressure drops on both sides of PHX. With the computed value of PHX pressure drop, sCO_2 cycle design was then iterated to provide a net output power of 2MW. In this final design, the sCO_2 flow rate is computed to be 48.1 kg/s and the overall cycle efficiency was found to be 20.3 %.

The microchannel PHX design is compact and the feasibility for fabrication with commercially available materials was established. The PHX thus complements the compactness of the overall system comprising the compact sCO_2 turbomachinery.

It is recommended that the commercialization path for the PHX as a component/subsystem include performance test validation of a scalable 500 kW thermal demonstration unit. The test includes pressure drop and heat transfer performance measurements of the fin structure as well as the etched channel artwork for the sCO_2 stream. One of the practical aspects of the heat exchanger operation that the test will help address is fouling mechanism of the exhaust stream, developing effective cleaning methods and cleaning intervals.

System level techno-economic studies are recommended for both retrofit and new plant applications, including life cycle costs, emission reduction assessments and payback periods, and comparing them against current practice. A commercialization roadmap is also required that would include other components/subsystems such as the turbomachinery.

Currently, there are sites in the US, Europe and Asia that would benefit from incorporating a waste heat recovery unit to their existing cement plants. Global and holistic decarbonization must include industries such as cement being considered in this paper as well as steel and others where waste heat needs to be utilized to improve overall operational efficiencies and environmental performance. For this reason, the results presented here have applications beyond the cement industry to meet he overall decarbonization objectives,

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