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IDENTIFYING WASTE HEAT IN STEEL INDUSTRY FOR CAPTURE UTILIZING SUPERCRITICAL CARBON DIOXIDE

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ABSTRACT

Supercritical carbon dioxide exhibits superior thermal capacity, in addition a high enough density to enable low-energy compression. By exploiting its incredible thermodynamic properties in a Brayton cycle, high temperature heat sources may be converted to power at a higher efficiency than conventional Rankine cycles. Analyzing the steel industry's waste heat sources, appropriate technologies are matched with their respective thermal sources to maximize the recovery of waste heat and minimize carbon emissions. The optimum cycle chosen, taking into consideration economic feasibility, power generation potential, and efficiency, is the simple regenerated cycle – reaching efficiencies of approximately 40% in comparison to 37% with a preheating cycle. Thermoelectric, thermoacoustic, and thermionic generators may be utilized to capture remnant low grade waste heat – supplemented by radiated energy captured by flat heat pipes and directed to a Trilateral Flash Cycle (TFC) for maximum waste heat recovery.

NOMENCLATURE

sCO_2 – Supercritical Carbon Dioxide
TFC – Trilateral Flash Cycle
WHR – Waste Heat Recovery
FHP – Flat Heat Pipe

1. INTRODUCTION

Nominal heat engine and plant efficiencies fall under 40%, with substantial waste heat rejected to the environment. The exergetic efficacy of waste heat is examined and characeterized as high, medium, or low grade heat. With respect to the second law of thermodynamics, a degree of waste heat must be rejected to the environment. Therefore, the focus will be on increasing exergetic efficiency by utilization of sCO_2 system cycles for high and medium grade heat waste recovery. Low grade heat is typically characterized as under 200°, with recovery methods typically utilizing temperature gradients with room temperature air or working fluids with low saturation temperatures. A major contributor to waste heat is the steel industry, responsible for over 4.79 PWh per year with over 14.16 PWh of absolute energy wasted globally after combustion [6]. To accelerate sustainability and the efficiency of utilizing heat sources for energy generation, the recovery of waste heat must be addressed.

Supercritical CO_2 has been a rapidly growing area of research for application in thermal power conversion. Supercritical fluids exist above the critical point and take on the simultaneous properties of liquid and gaseous states, enabling high density and mobility. Carbon dioxide transitions to the supercritical state above 31.1° C and 7.4 MPa, a highly attainable low temperature as displayed in Figure 1. One of the primary benefits of utilizing supercritical carbon dioxide is its incredible density at over 40% that of liquid water, leading to highly favorable thermodynamic properties.

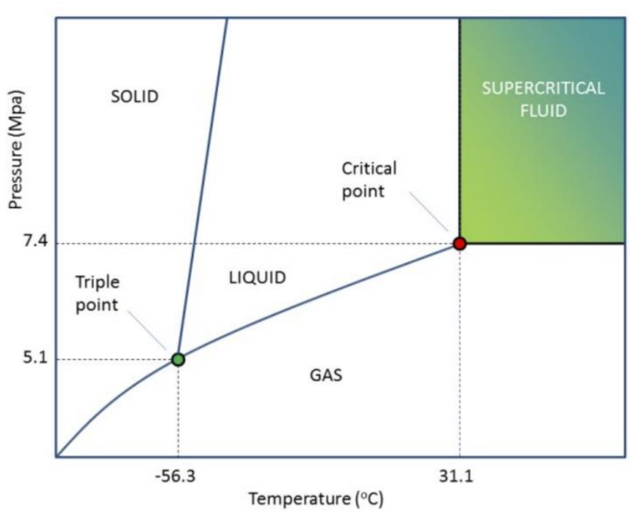

Figure 1 - Supercritical Carbon Dioxide Transition [3]

Higher density fluids require substantially less energy to effectively compress, therefore minimizing the required energy drawn from the turbine in a sample brayton cycle. The minimization of parasitic energy from the turbine enables high power-output and subsequently a high cycle efficiency. The low compressor inlet temperature maintaining the supercritical state enables high potential for thermal matching, as 31° C is nearly room temperature. Therefore, substantially higher temperature gradients can be achieved through the utilization of sCO_2 as a working fluid. In addition to highly advantageous thermodynamic properties, supercritical carbon dioxide is chemically stable and nonflammable – eliminating the need to utilize inert compounds in system development and the consideration of chemical corrosion. The incredible thermal harnessing capabilities of supercritical carbon dioxide is displayed in Figure 2, demonstrating the thermal capacity peak when supercritical conditions are achieved.

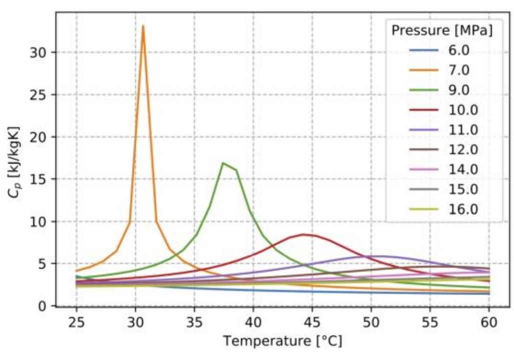

Figure 2 - Thermal Capacity of Carbon Dioxide

Perhaps the most incredible property of sCO_2 systems is their compactable nature derived from their high density – enabling over a 10x size reduction from traditional steam Rankine cycles. This leads to highly promising applications in modular nuclear reactors and other compact sources of energy generation in which thermal energy is produced. The Organic Rankine Cycle (ORC) is quite often utilized in industries with lower waste heat temperatures, typically most effective between 200 to 400° C. The supercritical carbon dioxide cycle becomes substantially more effective at higher temperatures, making it a prime candidate for even demonstration nuclear fusion reactors. The focus of the following paper will be high temperature molten slag waste heat recovery, discharged at over 1500° C. Numerous methods of recovering such waste heat will be covered, in addition to potential methods for recovering low-grade waste heat upon dispersion to environment via flue gases.

Low-grade heat recovery is potentially one of the most challenging areas of energy generative methods. Thermoelectric generators utilizing the temperature gradient between expelled flue gases and the ambient environment may potentially recover the remaining exergy. In addition, condensing economizers in applications with waste-water cooling, a common practice in the steel industry, may recover wasted heat and improve the plant's efficacy. However, an economic analysis must be performed to justify the cost to the increased efficacy. Another promising technology for low grade heat recovery is the trilateral flash cycle, utilizing a modification of the Organic Rankine Cycle to heat a working fluid to its saturation temperature. Avoiding evaporation, the cycle enables a minimum of 50%+ greater energy generation potential than the traditional ORC according to [1]. A simpler configuration can be equivalently achieved by utilizing thermoacoustic generators, achieving low efficiencies of up to 2% – but nonetheless, simple, and cheap to integrate according to [2].

For high-grade heat recovery, the primary focus will be upon the utilization of supercritical carbon dioxide cycles. However, another emerging technology is the utilization of flat heat pipes to capture energy over temperature ranges from 500 C to 1000+ C utilizing thermal radiation. The outer layer of the FHP absorbs the radiation, transferring it to the evaporator wall via conduction – enabling a direct heat transfer to the working fluid. Such a system has high applicability potential with molten slag in steel industry and cement plants due to the substantial amount of radiant heat naturally occurring throughout steel manufacturing processes. The heat potential recovery is outlined by the radiative heat transfer equation,

$$\dot{Q}_{rad} = \sigma \mathrm{A}\left(T_h^4 - T_s^4\right)$$

In which, σ is the Boltzmann constant, A is the heat pipe surface area, T_h is the temperature of the heat source, and T_s is the temperature of the heat pipe surface. As molten slag exits the casting machine in an orthodox steel manufacturing mill, the radiant heat may be captured utilizing a flat heat pipe heat exchanger with a working fluid such as water. Typical temperatures begin around 1200 C, reaching 120 C at the final conveyor through an average length of approximately 70 m. The flat heat pipe system from [4] is displayed below in figure 3.

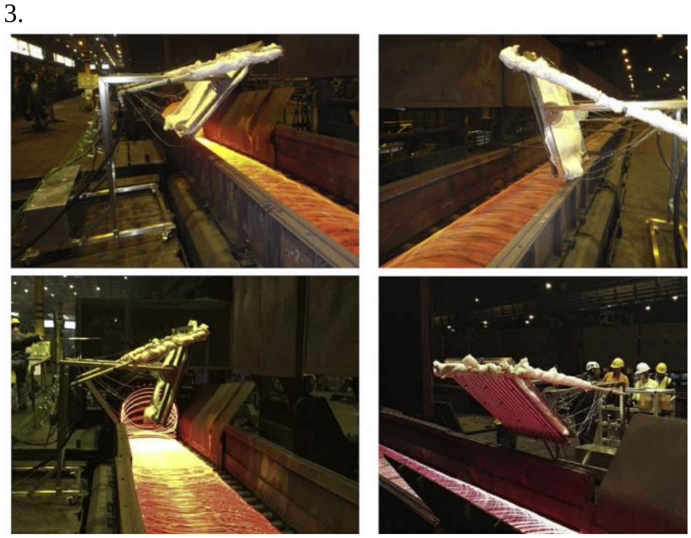

Figure 3 - Flat Heat Pipe System [4]

The proposed plan is to utilize flat heat pipe heat exchangers to capture radiative energy of molten slag as it exits the casting machine before it is fed to a primary granulator and heat exchanger for waste heat recovery utilizing supercritical carbon dioxide cycles. The remnant flue gases may be further exploited for exergy utilizing low-grade heat recovery methods, such as lined thermoelectric generators utilizing semiconductor material or thermoacoustic motors. The trilateral flash cycle, if economically viable to include, may prove highly promising to maximize the waste heat recovered from wasted low-grade temperature molten slag and other waste heat sources in the final stage of the manufacturing process. However, the focus of the following literature will be on outlining the sources of waste heat in the steel industry and exploring the various sCO_2 cycle layouts maximizing efficiency of the primary waste heat recovery.

2. MATERIALS AND METHODS

The recovery of waste heat from the steel industry requires an initial identification of potential sources of waste heat, followed by a description of recovery methods. The ideal operation temperature of a supercritical carbon dioxide system is approximately 500 to 700 degrees Celsius, with the most sensitive component to system efficacy being the turbine inlet temperature (TIT) according to a sensitivity analysis performed by [5]. The Organic Rankine Cycle (ORC) is satisfactory for medium temperature applications, but the sCO_2 cycle proves more efficient for higher temperatures. A full sensitivity analysis on various cycle parameters is displayed in Figure 5, demonstrating the second most sensitive factor in cycle efficiency is the compressor inlet temperature. Hence, to maximize the efficacy of the cycle, the appropriate sources of waste heat must be exploited for the appropriate WHR technology – in a method maximizing TIT for sCO_2 and utilizing the appropriate medium and low-grade heat source for other technologies. The primary forms of waste heat from the steel industry emerge from molten slag, hot water for cooling processes, and resultant flue gases. The primary heat source is molten slag, requiring the utilization of sCO_2 for effective heat recovery. Exiting hot water and flue gases may utilize thermoelectric generators, applying the Seebeck effect to generate a voltage gradient from a temperature gradient. The conduction through piping from hot water to ambient air can provide a satisfactory temperature gradient and can generate a substantial proportional voltage by utilizing semiconductor material to amplify the thermoelectric Seebeck coefficient. Another method of harnessing such low-grade heat utilizes thermoacoustic generators bouncing acoustic pressure waves to power a linear alternator. Lastly, a condensing economizer may be utilized to maximize recovered heat from the hot water and flue gases for reuse in the steel manufacturing process or for energy generation. A typical steel system layout is displayed below in figure #4.

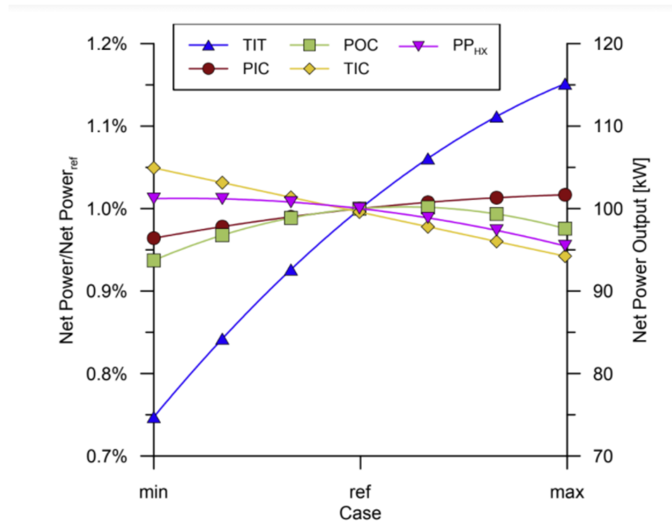

Figure 5 - Sensitivity analysis from [5]

2.1 Cycle Analysis

Example cycle efficiency calculation utilizes the turbine inlet temperature, pressure ratio between compressor inlet and outlet, and the efficiency of all components. The cycle can then be optimized utilizing various flowrates and split distributions for a variety of Brayton cycle layouts: simple regenerative (SR), reheating (RH), recompression (RC), recompression reheating (RCRH), split heat split expansion (SHSE), pre-heating (PH), pre-heating split-expansion (PHSE), and pre-heating pre-compression (PHPC).

An analysis performed by [6] compared the cycles, identifying their relative efficacies. The simple regenerated cycle tends to be the most economical, with re-heating and re-compression cycles offering greater power outputs by splitting the flow to pass through a recuperator and second heater. The split heating of the flow post compression enabled improved thermal matching between carbon dioxide working fluid and the heat source. The secondary expansion work draws more power from the same input heat source, therefore increasing efficiency. In the re-compression configuration, the flow is split in the low-pressure segment of the cycle into a primary and secondary flow. The main flow is then cooled and compressed through the primary compressor as the secondary flow bypasses cooling and is directly compressed before rejoining the primary flow. Such a split configuration enables improved thermal matching

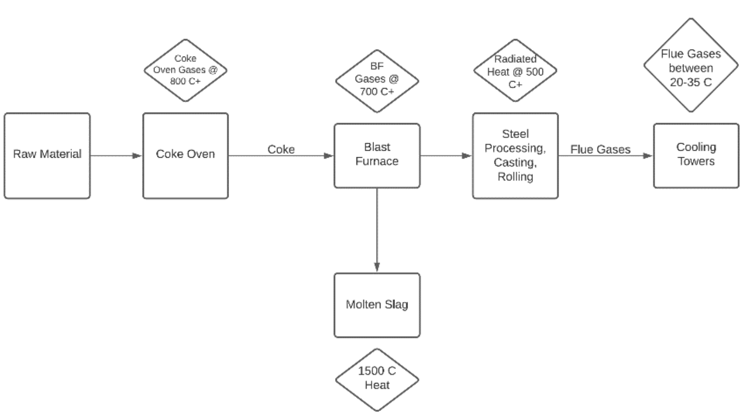

Figure 4 – Steel Industry Flowchart

while simultaneously decreasing the magnitude of heat rejected to the environment via a cooler. The re-compression re-heating cycle layout (RCRH) combines both layouts, leading to a higher cycle efficacy at the expense of higher complexity, and therefore, less economic feasibility. The least complex configuration utilizes the pre-heating cycle, splitting the flow downstream the compressor into two flows individually traveling through the recuperator and a pre-heater. The flows later recombine and travel through the primary heater before expanding through the turbine for work extraction. Such an arrangement enables superior thermal matching and a higher utilization of heat. The pre-heating (PH) with split expansion (PHSE) and split heating with split expansion (SHSE) both split their respective flows downstream the compressor and acquire heat in separate, p arallel branches before expanding in separate turbines for work extraction. Albeit the system achieves a higher efficiency, the configuration may not be as feasible due to the increased complexity. Figures 6 below illustrates the various cycle layouts from [6].

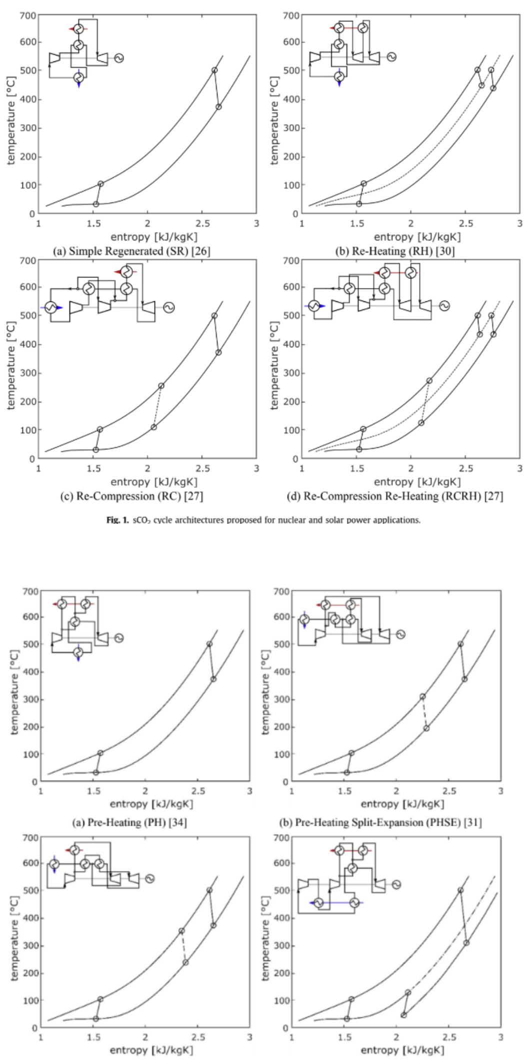

Figure 6 – Cycle layouts from [6]

Values, in accord to [6], for SHSE, PHSE, PH, and PHPC layouts produced 124 kW, 165 kW, 171 kW, and 174 kW respectively compared to 95 kW, 98 kW, 113 kW and 115 kW generated by RH, RCRH, RC, and SR respectively. The highest net power output was accomplished by the PHPC configuration. However, the most economic design was found to be the simple regenerated cycle at $770/kWe and a payback period of 1.86 years. Hence, the designer must compare economic efficacy with energy regeneration efficacy. As cycle efficiency increases with complexity, the respective investment costs displayed a parabolic increase with the highest IRR ranging between 325 C and 500 C due to the high expense of the heat exchangers. Thermodynamic analysis demonstrated SR, RC, and PHPC to have the highest 1st law efficiency above 400 C turbine inlet temperature, with SR achieving the highest efficiency by a small margin. A thermodynamic analysis of the net power output relative to turbine inlet temperature

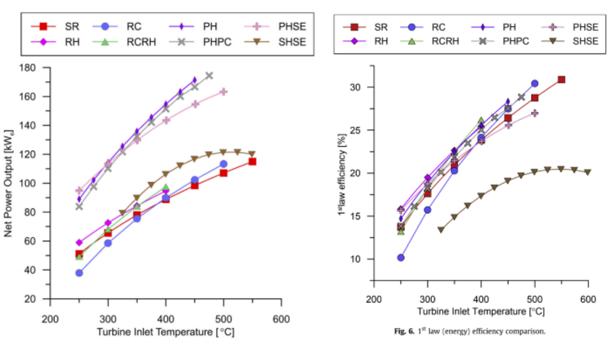

Figure 7 – Net power & first law efficiency from [6]

demonstrated the highest power output is accomplished utilizing PH and PHPC – marginally higher than the SR, RC, and SHSE cycles as displayed in Figure 6 from [6].

2.2 Molten Slag Recovery Methods

Molten slag is the remnant, rocky material leftover from the steel ore extraction process upon exiting the blast furnace. To increase the heat transfer efficacy, the slag must be granulated into finer particles to assist air convection before feeding into a heat exchanger. According to [8], for every three tons of hot metal produced, approximately a ton of molten slag at 1500 C is discharged – responsible for approximately 1.8 GJ of unrecovered waste heat. Efficient heat recovery therefore requires slag granulation, disintegrating the particles into minute droplets before solidification with air. The common, studied forms of dry granulation are air blast granulation, rotary drum(s), and spinning disk/cup. The heat is then extracted utilizing air as the working fluid from the droplets or from the solid granulates. [8]

proposes a highly effective method of dry granulation utilizing a spinning disk, atomizing molten slag to miniscule droplets to enable rapid cooling below 900 C to be followed by solidification. Next, the slag granules are cooled utilizing a packed bed counter flow heat exchanger before discharging at 25-50 C. The exiting air may be utilized for various processes, as displayed in figure 8, with the primary focus to be for power generation utilizing sCO_2 cycles.

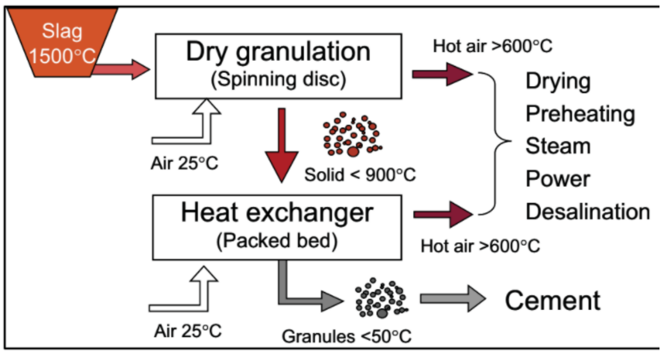

Figure 8 - Molten Slag Granulation from [8]

2.2 RADIATION CAPTURE

Heat pipe design utilizes heat recovery by thermal radiation from sources at temperatures greater than 500 C. Radiation is absorbed by the surface of the FHP and transferred via conduction to the evaporator wall, where a working fluid vaporizes and flows to the condenser through insulated adiabatic tubing. The heat may then be transferred to a cooling fluid utilizing a shell and tube heat exchanger. Figure 9 below demonstrated the concept from [4].

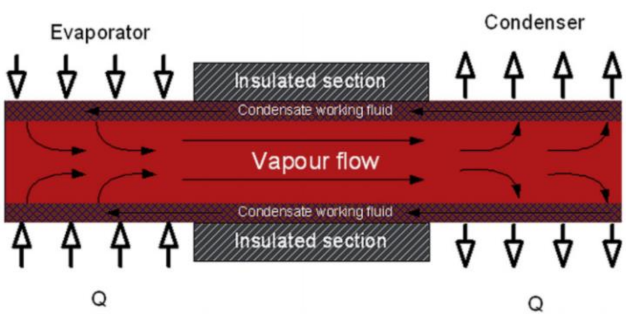

Figure 9 - Flat Heat Pipe

Industrial testing demonstrated a heat recovery of 5 kW, with a potential of up to 10 kW for a meter long segment of the device. Nominal production lines are approximately 70 m long, indicating up to ¾ of a MW may be recovered in an industrial plant. With nominal temperatures of transported steel ranging from 1200 C upon exit from the rolling mill to 120 C through the conveyor at the laying bed, up to 1.6 MW may be theoretically recovered from each conveyor assuming a heat recovery efficiency of 75% and FHP surface temperatures of 100-191 C at 5 lines of conveyors per plant. The working fluid utilized by [4] is water, with an outlet temperature maximum reaching up to 45.3 degrees Celsius. Other working fluids may increase the captured thermal energy, with additional modifications to the heat exchanger. The design utilizes gravity to transfer the fluid, therefore requiring an angled placement. To maximize radiative heat transfer, the FHP may be placed horizontally – utilizing a wick to transfer the working fluid to perhaps increase its temperatures up to an optimistic 100 C. Such temperatures may then be employed by a TFC [9] for individual heat recovery or employed in preheating sCO_2 cycles. Alternatively, the FHP's may be primarily placed only in segments where the steel transport temperatures are between 1200 – 900 C, as [4] assumes temperatures of 500 C.

2.3 Cycle Calculation Methodology

Integrating CoolProp with MATLAB enables the utilization of a library of working fluid properties for calculations – including entropy, enthalpy, and temperatures at given parameters. Utilizing a known TIT, pressure ratio, compressor and heat exchanger efficiencies, and a starting temperature, the remaining temperatures of the cycle may be extracted. A sample cycle calculation for simple regenerated is demonstrated in Figure 10 below.

```
p2=40*10^6; t1=32+273; tit=700+273; t_eff=0.85; c_eff=0.7; r_eff=0.9; flowrate=48;
p1=7.8*10^6
pr=p2/p1

%compressor work
s1=py.CoolProp.CoolProp.PropsSI('S', 'T', t1, 'P', p1, 'co2')
h1=py.CoolProp.CoolProp.PropsSI('H', 'T', t1, 'P', p1, 'co2')
h2i=py.CoolProp.CoolProp.PropsSI('H', 'S', s1, 'P', p2, 'co2')
h2r=((h2i-h1)/c_eff) + h1
s2=py.CoolProp.CoolProp.PropsSI('S', 'H', h2r, 'P', p2, 'co2') %optional
t2=py.CoolProp.CoolProp.PropsSI('T', 'S', s2, 'P', p2, 'co2') %optional
comp_work=flowrate*(h2r-h1)

%turbine work
s4=py.CoolProp.CoolProp.PropsSI('S', 'T', tit, 'P', p2, 'co2')
h4=py.CoolProp.CoolProp.PropsSI('H', 'S', s4, 'P', p2, 'co2')
h5i=py.CoolProp.CoolProp.PropsSI('H', 'S', s4, 'P', p1, 'co2')
h5r=-1*(t_eff*(h4-h5i) - h4)
turbine_work=flowrate*(h4-h5r)

t3=(121.7+273); t5=175.6+273; t6=76.8+273;
s6=py.CoolProp.CoolProp.PropsSI('S', 'T', t2, 'P', p1, 'co2')
h6i=py.CoolProp.CoolProp.PropsSI('H', 'S', s6, 'P', p1, 'co2')
h6r=-1*(r_eff*(h5r-h6i) - h5r)
h3r=((h5r-h6r)+h2r)

%Heat Added & Removed
q_in=flowrate*(h4-h3r)
q_out=flowrate*(h6r-h1)

%Regenerated Heat (Reg Heat)
q_reg=flowrate*(h3r-h2r)

%Net Power
P_net=turbine_work - comp_work

%Efficiency
efficiency=P_net/q_in
%or
eff_2=1 - (q_out/q_in);
fprintf('The cycle efficiency is %.1f%%', efficiency*100)
```

```
p1 = 7800000
pr = 5.1282

s1 = 1.3262e+03
h1 = 3.0027e+05
h2i = 3.4336e+05
h2r = 3.6182e+05
s2 = 1.3777e+03
t2 = 363.9271
comp_work = 2.9543e+06

s4 = 2.8055e+03
h4 = 1.2178e+06
h5i = 9.4437e+05
h5r = 9.8539e+05
turbine_work = 1.1157e+07

s6 = 1.9794e+03
h6i = 5.0899e+05
h6r = 5.5663e+05
h3r = 7.9058e+05

q_in = 2.0508e+07
q_out = 1.2305e+07

q_reg = 2.0580e+07

P_net = 8.2031e+06

efficiency = 0.4000

The cycle efficiency is 40.0%
```

Figure 10 –Simple Regenerated Cycle Calculation

The turbine work, compressor work and total heat added may then be calculated for the final cycle efficiency and total energy generated. The parameters may then be fine tuned to maximize efficiency and power generated.

3. RESULTS AND DISCUSSION

For the simple regenerated cycle, assuming no preheating, a TIT of 700 C with a pressure ratio of 5.13, and turbine, compressor, and recuperator efficiencies of 85%, 70% and 90% respectively, the net power generated is 8.20 MW at an efficiency of 40%. The highest efficiency is accomplished by maintaining the compressor inlet pressure at 7.8 MPa, near the critical point of sCO_2. Incrementing the outlet pressure increases the total work done by the compressor but enables higher work extraction from the turbine at a higher efficiency. Incrementing the pressure outlet higher than 40 MPa enables even higher power outputs – but may strain the compressor material and sacrifice economic feasibility. At an outlet pressure of 70 MPa, the efficiency remains at 40% with an extracted net power output of 9.25 MPa – an order of magnitude higher. Increasing past 80 MPa begins to sacrifice efficiency for relatively little net power output gains. Hence, a balanced outlet pressure to avoid mechanical stresses on components is at approximately 40 MPa. The turbine inlet temperature is maintained at a maximum temperature of 700 C, as higher temperatures will induce thermal and mechanical strains on turbine components and sacrifice longevity. The flowrate of sCO_2 is assumed to be 48 kg/s. Increasing the flowrate considerably increases the net power output, with negligible effect on cycle efficiency. However, higher flow rates require a parasitic drain on compressors and may require additional parasitic drains through usage of pumps.

The pre-heating cycle utilizing the captured radiated heat as the initial heat source as in Figure #12 yielded a considerably higher efficiency when most of the flow was routed through the recuperator. As the temperature of the flow through the recuperator far exceeded the temperature of the heater, H1, the cycle efficiency did not increase – albeit the added heat to the system. Therefore, a cycle with most of the flow routed through the recuperator can more optimally be replaced with a simple regenerated Brayton cycle. With the highest economic feasibility, and similar power generating ability, the simple regenerated cycle is the superior cycle when lacking a satisfactory heat source.

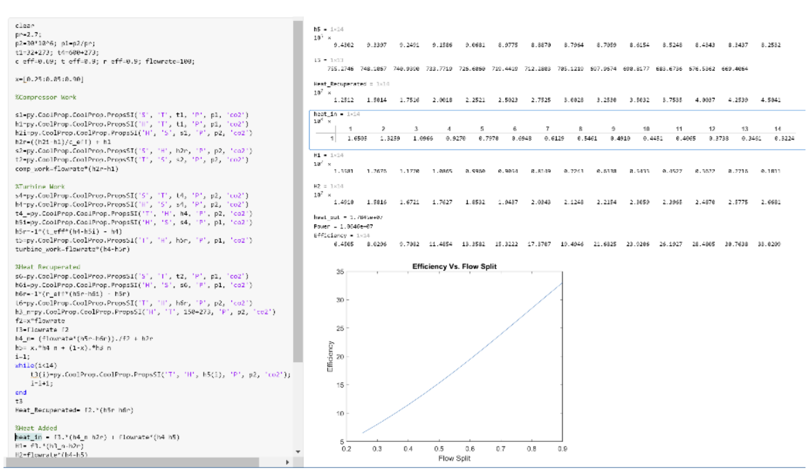

Figure 11 - Pre-Heating Cycle Split Calculation

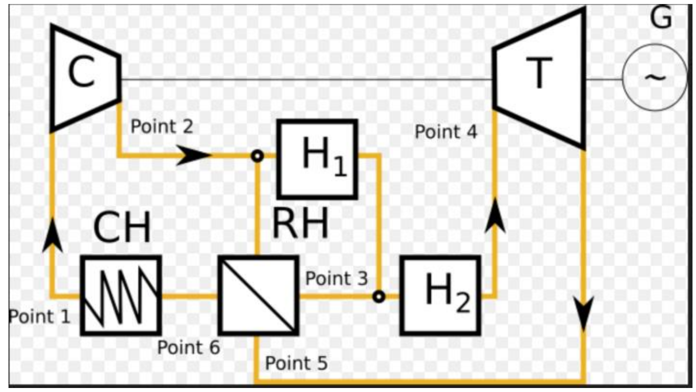

Figure 12 –Preheating Cycle

4. CONCLUSION

Waste heat from the steel industry may be recovered utilizing supercritical carbon dioxide Brayton cycles and supplemented by thermoelectric generators, thermoacoustic engines, and the Trilateral Flash Cycle (TFC) for low temperature (<200 C) heat recovery. Coke oven gases, reaching temperatures greater than 1000 C, are routed through a heat exchanger to function as a heater for a supercritical carbon dioxide Brayton cycle. Exiting the blast furnace, the remnant molten slag after the steel ore extraction process is granulated to amplify heat transfer and recovered utilizing a cross flow heat exchanger leading to a supercritical carbon dioxide Brayton cycle. Heat radiated away during the transportation processes may be recovered utilizing a flat heat pipe (FHP) and routed for either pre-heating or individual power generation, with flue gases utilized for cooling retaining too little exergy for useful power generation. Hence, flue gas exergy may be recovered utilizing thermoelectric and thermoacoustic generators. The ideal Brayton cycle identified for recovery is the simple regenerated cycle, offering significantly more economic feasibility for comparable power.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Iqbal, M. A., Rana, S., Ahmadi, M., Date, A., & Akbarzadeh, A. (2019). Trilateral Flash Cycle (TFC): a promising thermodynamic cycle for low grade heat to power generation. *Energy Procedia*, *160*, 208–214. https://doi.org/10.1016/j.egypro.2019.02.138

[2] Kalid O.A., Abdoulla-Latiwish, Xiaoan Mao, Artur J. Jaworski, (2017), Thermoacoustic micro-electricity generator for rural dwellings in developing countries driven by waste heat from cooking activities. *Energy, 134- 1107-1120*, https://doi.org/10.1016/j.energy.2017.05.029

[3] *Supercritical CO_2*. Suprex. (n.d.). http://www.suprex.uk/supercritical-co2.

[4] Jouhara H, Almahmoud S, Chauhan A, Delpech B, Bianchi G, Tassou S A, Llera R, Lago F, Arribas J J. "Experimental and theoretical investigation of a flat heat pipe heat exchanger for waste heat recovery in the steel industry," Energy, vol. 141, pp. 1928–1939, Dec. 2017.

[5] Wang, X., & Dai, Y. (2016). Exergoeconomic analysis of utilizing the transcritical CO2 cycle and the ORC for a recompression supercritical CO2 cycle waste heat recovery: A comparative study. *Applied Energy*, *170*, 193–207. https://doi.org/10.1016/j.apenergy.2016.02.112

[6] Marchionni, M., Bianchi, G., & Tassou, S. A. (2018). Techno-economic assessment of Joule-Brayton cycle architectures for heat to power conversion from high-grade heat sources using CO2 in the supercritical state. *Energy*, *148*, 1140–1152. https://doi.org/10.1016/j.energy.2018.02.005

[7] Zhang, S. (2019). Pilot study on ascension-pipe heat exchanger used for waste heat recovery of coke oven gas. *Energy Procedia*, *158*, 26–31. https://doi.org/10.1016/j.egypro.2019.01.029

[8] Xie, D., & Jahanshahi, S. (2008). Waste Heat Recovery from Molten Slags. *4th International Congress on the Science and Technology of Steelmaking*.

[9] Iqbal, M. A., Rana, S., Ahmadi, M., Date, A., & Akbarzadeh, A. (2019). Trilateral Flash Cycle (TFC): a promising thermodynamic cycle for low grade heat to power generation. *Energy Procedia*, *160*, 208–214. https://doi.org/10.1016/j.egypro.2019.02.138

[10] Falcao, E., & Ribeiro, G. (2019). Thermodynamic optimization of a heat exchanger used in themal CYCLES applicable for Space Systems. *Proceedings of the 25th International Congress of Mechanical Engineering*. https://doi.org/10.26678/abcm.cobem2019.cob2019-0540

[11] *Supercritical co2 tech team*. Energy.gov. (n.d.). https://www.energy.gov/supercritical-co2-tech-team.