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Analysis of a CO_2 blended fluid based EGS cycle and its implication for highly efficient low grade geothermal power generation system

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ABSTRACT

The economy of water based Enhanced Geothermal System affect it's utilization compared to other renewables largely due to the phys-chemical properties of water. CO_2 captured from energy industry is a promising substitution to replace water. A novel design approach is proposed to maximize the thermodynamic efficiency of Enhanced Geothermal System tapping into low grade geothermal reservoirs. CO_2 regenerated from stripper tower is condensed and collected into a subcritical, liquid form, it absorbs heat from geothermal reservoir and becomes supercritical. In the combined effect of geothermal and gravitational field, it rises back from the production well and is blended with another working fluid with unequal pressure. Undergoing heat and mass transfer to another saturated or subcooled working fluid (primarily an organic working fluid) in direct contact, the supercritical CO_2 expands while the secondary liquid vaporizes, creating a binary species fluid expanding across the expander(s). Heat transfer between both species may bear the potential of raising power output significantly, and results in a polytropic process with a polytropic index closer to 1 compared to that of an adiabatic process. Simple calculation with separate flow method has demonstrated that majority of the power generated comes from the latent heat of the second working fluid experiencing phase change. And design of the compression stage coupled with gravity of CO_2 effectively reduces energy consumption to bring CO_2 back to liquid state, while making enough room for separation of fluids. Such novel design schematics is able to generate power from very low temperature, e.g., 50℃ $scCO_2$, in large scale deep wells, while taking care of CO_2 geological storage simultaneously. The proposed scheme can improve the economy of geothermal power system.

1. INTRODUCTION

CO_2 based Enhanced Geothermal System, or EGS, for tapping in hot dry rocks having rare naturally occurred cracks and with almost no ground water, have been proposed in the first decade of this century[1]. It has emanated a shining beacon of light, refreshing our mind of how geothermal systems, especially how geothermal power generations system may work together with ORC, with CCUS and with Enhanced Oil and Gas Recovery. But, the properties of CO_2 itself have brought new challenges for people who are eager to see a breakthrough on the horizon, which may open new epoch for the geothermal energy to be ubiquitously available and produce energy and electricity with zero or even negative carbon footprint. CO_2-Plume Geothermal (CPG) has also been proposed and studied for shallower reservoir (modeled to be 2.5km)[2], whose rock formation has higher porosity and natural crack development, having decent heat mining networks within the matrix.

CO_2 based EGS and CPG have many advantages over the water based system in that: 1. CO_2 have a much lower viscosity and much stronger thermal and mass diffusivity, thereby being capable of permeating into fractures with greater surface area and carrying more heat out of geothermal reservoir. 2. Thermosiphone effect of CO_2 makes it easier to carry thermal energy to the ground surface without additional pumping requirement, saving for parasitic power otherwise required in a heat mining system. Thus, much greater mass flow rate, and consequently a higher heat transmission rate is achieved when using CO_2 instead of water from the reservoir. 3. the solvation power of supercritical CO_2 to salts and minerals at downhole condition is much less than that of water, thus having little problems such as clogging, etching, rusting for the maintenance of pipes, valves, turbines and other mechanical parts in a surface plant. The disadvantage of CO_2 however, lies in the fact that its temperature may decreases as it expands in horizontal well and rises back to the surface owing to its enthalpy decline and throttling losses. If the temperature becomes too low prior to entering power cycle, even the most responsive ORC system will not work when using conventional heat exchanger to recover the heat carried by the geofluid. Thus a more decent power generation method needs to be invented to utilize the energy stored in low temperature supercritical CO_2 .

The utilization of CO_2 also has drastic advantage of water saving compared to water based EGS, and its environmental and economic benefit will be enlarged in accordance with the advancement of CO_2 capture, utilization and geological storage (CCUS). Conventional CO_2 capture from coal fired power plant adds additional $50 for each tonne of carbon captured and buried[3]. For a single pair of wells, thousands of tonnes of carbon can be re-utilized to generate power in a few decades, therefore contributing to lessened cost of capturing CO_2, leaving more economic options for coal miners, owners of power plants and oil/gas industry to make business more economically viable. Likewise, Enhanced Oil and Gas Recovery (EOR) can apply the same strategy when crude oil or natural gas is depleted.

2. THE STATE-OF-ART CO_2 BASED GEOTHERMAL SYSTEM AND THEIR PERFORMANCE

The problems facing CO_2 as the working fluid for direct expansion system are given: For example, as the CO_2 rises up to the surface ground, CO_2 flow in one direction against the frictional force exerted by surrounding rocks and expands, leading to enthalpy decrease of CO_2 and subsequent temperature drop. Consequent temperature of CO_2 less than that of water may be found at the production well head. Under such conditions, a direct expansion system of CO_2 produced very limited power, since the turbine inlet temperature is too close to the environment temperature. And CO_2 cannot expand to very low pressure because of the condensation problem. At 6MPa, saturation temperature of the CO_2, namely, 295.13K or 21.98℃ makes it difficult to be condensed by solely giving off thermal energy to the environment in a whole year operation in most regions within 30 degree latitude across the globe. If condensation does not occur, gaseous CO_2 may not be able to spontaneously return back to the geothermal reservoir due to its low density inside the injection well, making the thermosiphon ineffective and the failing of the underground heat mining cycle. Besides, the sole adiabatic expansion of supercritical CO_2 to gaseous state does favor a decent turbine design, due to the very large ratio of specific heats C_p/C_v comparing to other refrigerants and sharp variation of this value when closer to critical point. These drawbacks severely limit the application of CO_2 in direct power generation within geothermal energy and other low-grade heat recovery scenarios. Successful cases using CO_2 as working fluid, including Echogen, supercritical CO_2 Brayton Cycle on Concentrating Solar Power (CSP), and Allam Cycle, have involved high grade heat source, ensuring temperature at inlet of expanders higher than 500 ℃ in most cases. There are also lower temperature applications, for example, the research conducted at Sandia National Laboratory, using CO_2 based mixture (supercritical) Brayton Cycle to generate power-- a novel approach to temper the properties of CO_2 to be more adaptable to low temperature heat source [4]. However, its optimum temperature range in operation for turbine inlet was no less than 160 ℃. This temperature still poses high requirement for its intended use in geothermal power generation in the US, and cannot be easily fulfilled in most geothermal sites in China.

The patent, filed on 1999 Sept. 10. by Donald W. Brown (US 6,668,554 Bl) stating that ORC is superior than direct CO_2 expansion system in terms of the thermodynamic efficiency--a factor of 3 can be achieved when ORC is utilized instead of direct CO_2 expansion system. ORC is a mature technology for geothermal power generation and low grade heat recovery. Many successful cases have been applied in heat resources having temperature around 100℃. But examples of tapping thermal energy with temperature less than 70℃ is rare, since Carnot efficiency for such heat source and ambient environment is very limited.

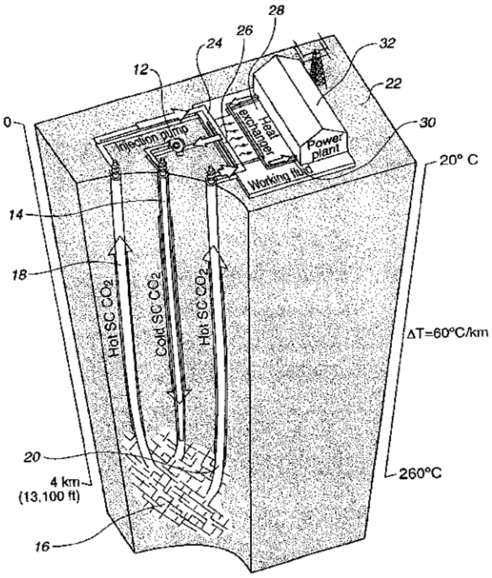

Figure 1- D. W. Brown's patent showing the concept of using CO_2 and ORC dual cycle to generate electricity in EGS.

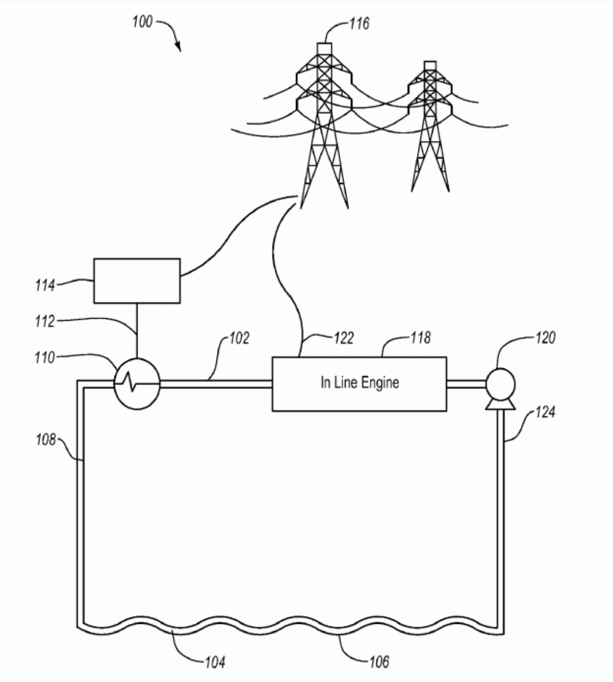

Figure 2- A step further made by Muir and Eastman: direct CO_2 expansion is in parallel layout with ORC.

In the year 2011, John R. Muir, Alan D. Eastman, and Mark P. Muir had proposed an interesting design (US2011/0100002A1), based on the dual cycle system utilizing CO_2 and organic working fluid. This approach has taken into account the thermal energy left in the CO_2 after its heat transfer to the organic working fluid. The near isobaric heat exchanging process occurs at a pressure appreciable higher than that at the inject wellhead, thereby leading to a significant entropy reduction of the CO_2 before its subsequent expansion. As a result, even with a turbine having 75% isentropic efficiency, the expansion is able to create saturated, medium to high quality CO_2 at the turbine outlet, meaning that a crucial amount of CO_2 will be condensed before entering a condenser and a lessened load for the condenser. Furthermore, the expansion of CO_2 from supercritical state to saturated state, produces extra power adding to the system output. On the other side of the heat exchanger, organic working fluid serves as the direct coolant to pre-cool the CO_2 while undergoing its own phase change from liquid to saturated or superheated vapor, ready to expand in a low temperature organic steam turbine. After expansion, the vapor at lower pressure chamber can be superheated, saturated dry steam, or saturated wet steam, based on the species of organic fluids selected.

However, it worth mentioning that supercritical CO_2 has far less heat capacity than many liquids. Hence during heat transfer, a sharp decrease of temperature may be encountered. This is especially the case when the other side is organic working fluid undergoing evaporation (an isothermal process), leading to exergy destruction. The evaporation will not continue if heat transfer from the CO_2 to the organic fluid stops. And rate of heat exchange or heat flux delivered with heat exchanger is positively correlated to the temperature difference between CO_2 and the organic. These conditions set limits to the maximum temperature of the organic fluid and flow rate of organic species. And limitations of combining CO_2 based geothermal cycle with ORC can be clear seen.

Hereby the work of B. M. Adams, T. H. Kuehn and other scholars were cited, to conduct a theoretical study of the thermal cycle design of the CO_2-based geothermal system, upon which value of the CO_2 temperature, pressure, density and mass flow rate at each specific point of the heat mining cycle is determined by **REFPROF 9.0** for a geothermal system having a given downhole structure running on pure CO_2. With a geothermal gradient of 35℃/km, injection and production wells 2.5km deep and 0.71km injection-projection well spacing were selected to decide the state of CO_2 at the injection and production wellheads[5]. The production well follows a hypotenuse path of a right triangle confined by these wells.

Assuming temperature of downhole CO_2 is the same as reservoir temperature, 102.5℃ reservoir only yields geofluid of 50℃ at the production wellhead, quite low even for conventional ORC. What about direct expansion of CO_2? Regardless of the energy consumption during cooling and condensation, the highest thermodynamic efficiency gives 7.85% for direct CO_2 expansion system based on an isentropic efficiency 0.8 and 0.75 for the compressor and turbine respectively (Table 1). However there are two major problems for the direct expansion system: 1. property change during adiabatic expansion of CO_2 makes the turbine inefficient, leading to waste of useful work. 2. Cooling of CO_2 from gaseous state to liquid state significantly increase the load of condenser. Due to the limit of ambient temperature, CO_2 expanding to very low pressure (below 5 MPa) faces the challenge of condensation.

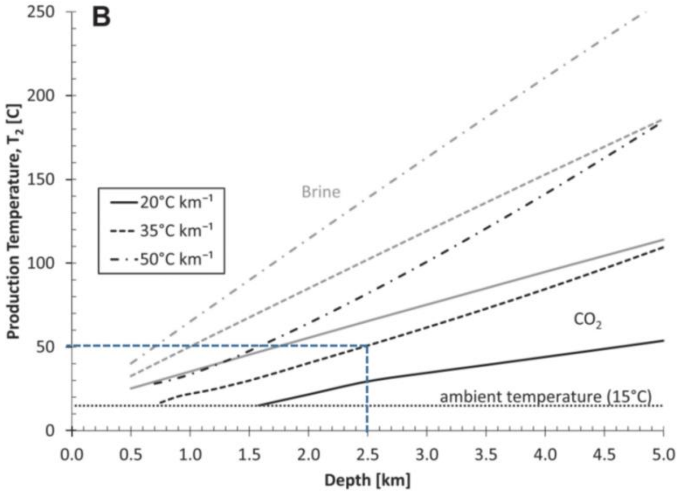

Figure 3- Temperature of CO_2 at the production well head based on CGP model by B. M. Adams et al.

Table 1- Maximum efficiency and power generated with no extra pumping of CO_2 in direct expansion of CO_2

Pressure Parameters		Maximum possible efficiency (assuming full condensation of CO2 in condenser with no extra energy cost)	mass flow rate(kg)	Enthalpy difference(kJ/kg)	Maximum power output （MW）
Pressure at the production wellhead	9.6 MPa	--	285	--	--
Direct expansion to given pressure	7.3 MPa	6.46%	285	85.68	1.57
	6 MPa	7.85%	285	133.95	2.997
	5 MPa, 7.3MPa	0.37%	285	86.68	0.0914

After going over the direct expansion approach, simple calculation were performed using Muir's approach. Primary estimation were made to decide the mass flow ratio between the CO_2 and the organic fluids. For Isobutane, Propane and R22, mass flow ratio of 1:4 and 1:5 were found to be acceptable to make the Muir's invention work. For Isobutane and Propane, mass ratio 1:5 was found to be most appropriate to conduct the estimation due to their large heat of vaporization at low temperature range. Judging from the results in table 2, it is worth pointing out, even though the thermal efficiency of pure organic cycle may be higher than that of the direct CO_2 expansion option, the low mass flow rate makes the cycle far from productive.

Table 2- Maximum energy produced from 1 kg of CO_2 when direct expansion and ORC are applied.

1kg/s CO_2 entering the power cycle with no extra compression. Isobutane, Propane and R22 on the other side of heat exchanger are selected for the ORC.	Energy produced from Organic	Energy produced from CO_2 (KJ/kg)	Combined Energy output
Isobutane (0.2kg)	4.4	5.83	10.23
Propane (0.2kg)	3.24	5.86	9.1
R22 (0.25kg)	2.34	6.89	9.23
CO_2 direct expansion to 6MPa	--	--	10.51

Energy produced by CO_2 was calculated by assuming the pressure to be 6MPa at the turbine outlet. CO_2 at 50℃ (323.15K, 9.6MPa) will first transfer heat to the organic fluid via an infinitesimal pinch heat exchanger (as if the organic and the CO_2 are in direct contact- which is not possible in reality but meaningful in the study) and then drop to 21.98℃, (295.13K, 6MPa) during expansion process, and power output of organic fluids were estimated separately, assuming they expand to a temperature approximately 295 K as well (assuming condensable by ambient environment). And 75% of energy was converted to work during isentropic expansion.

In the calculation conducted above, energy produced from the expansion of both CO_2 and the organic working fluid is the addition of energy produced from both branches, a typical “1+1=2” mode. From this table, it is clear to be seen that simply by combing transcritical CO_2 cycle with ORC does not increase the power output of low grade geothermal power generation system, even with the best heat exchanger ever possible. It is also observable that only a small portion of energy harvested from geothermal reservoir are obtainable by expanders. Appreciable amount of heat is wasted as latent heat in vaporizing the organic liquids.

Interestingly, according to Dalton’s law on ideal gas, mass ratio of CO_2 to propane, namely 5:1 indicates an equal ratio of the partial pressure of the two species (since their molecular mass is almost equal). In order to drop to 295.61K, partial vapor pressure of propane needs to decrease to 0.856MPa from its own expander. However, if propane expands together with CO_2, 6MPa partial pressure of CO2 gives the partial pressure of the organic vapor, which is 6/5 = 1.2MPa. Saturated propane at 1.2 MPa has higher temperature than that of CO_2 at 6MPa, implying that heat transfer from the propane vapor to CO_2 will occur. Indeed, propane vapor will continuously expand and condense in simultaneous expansion of CO_2 if they are both present closely in a gaseous mixture inside mechanical parts. This judgement gave us insights of how the latent heat of the organic vapor may be utilized in a novel fashion: If a subcooled or saturated liquid organic working fluid is added to CO_2 before the expansion, thermal energy will transfer from CO_2 to the organic. Hence the organic may boil and vaporize, becoming saturated or superheated vapor serving as a thermal reservoir giving off heat back to CO_2 in their subsequent expansion. More power output seems to be generated due to the mutual thermal energy exchange between the two species when combining this two routes into a single, coherent design.

3. CALCULATION AND ESTIMATION OF THE TRANSCRITICAL CO_2-ORC COMBINED CYCLE

In order make this model more clear, a system diagram was devised to depict the transcritical-ORC combined cycle, followed by a simple calculation. The calculation was performed prior to any strict simulation was carried out to the fluids’ mixture, thus only serving as a framework to unveil the mechanism of how such system may work when the temperature is too low to conventional ORC based on the principles of thermodynamics. Assumptions made in the calculation includes:

a) Two species in the mixture are undergoing expansion separately

b) Infinitesimal heat exchanging rate between two species during expansion with no requirement on the minimal terminal temperature difference

c) Pressure of each species remains before and after their blending in the jet pump, or ejector.

d) The back pressure (pressure after expansion stage and before condensation stage) of this transcritical cycle are composed of partial pressure of two species, whose values are determined in compliance with Dalton law of partial pressure.

e) The expansion of both species takes approximately equal time to reach their final states.

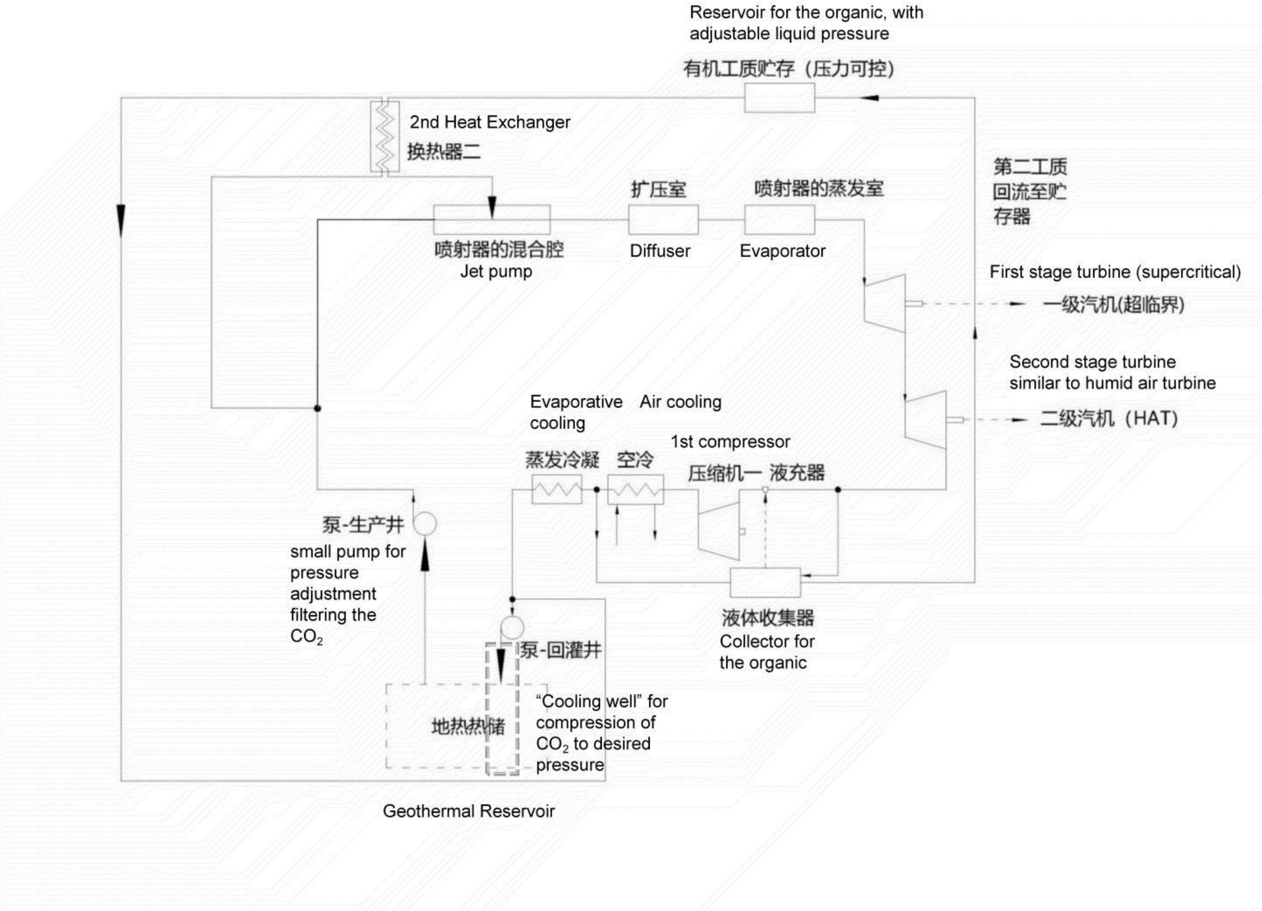

Figure 4- Schematic design of the CO_2-ORC combined cycle

Table 3- important states of CO_2 and propane in the CO_2-ORC combined cycle

	Pressure (MPa)	Temperature (K)	Specific enthalpy (KJ/kg)
Injection wellhead: liquid CO_2	7.3	303.67	311.12
Production wellhead: supercritical CO_2	9.6	323.15	396.80
After blending: supercritical CO_2	9.6	314.99	335.39
Expander outlet: gaseous CO_2	5	287.43	327.08
Propane before blending (saturated liquid)	1.3694	313.15	307.16
Propane After blending (superheated vapor)	1.3694	314	616.14
Expander outlet: Propane vapor	1	301.39	605.33

The 9.6MPa pressure of supercritical CO_2 at the production well is estimated by using the average specific inverse mobility of CO_2 taken to be nearly 22 kPa.s.kg^{-1}, and the pressure head loss due to overcoming the frictional force of the reservoir and wells are taken into account. Minor pressure drop at the production wellhead due to the kinetic energy of moving CO_2 is also subtracted from the total pressure.

The saturated liquid of propane is achieved by heating up propane from 30.29℃ (303.44K) to 40℃ (313.15K) with heat supplied also from supercritical CO_2 rising from the production well, using a relatively small heat exchanger. Its pressure is lifted by a liquid pump from around 1MPa to 1.3694MPa, which consumes negligible work with a 0.8 isentropic efficiency. Propane is at liquid state till its exiting the heat exchanger, so pinch point in a regular heat exchanger that usually occurs in organic vapor cycle was ruled out in the heat exchanging process: the phase change only occurs after its blending with the supercritical CO_2.

According to Adams et al.'s study, the upper limit of mass flow rate caused by thermosiphon effect of CO_2 with no extra pumping requirement is about 285kg/s, among which a minor stream is utilized to transfer heat to the organic. It is reasonable to assume mass ratio of the minor CO_2 stream to the organic to be 1:1, which can maintain the minimal pinch difference to be higher than 5 ℃. We also found that mass ratio of the major CO_2 attending the power cycle to the organic should be no less than 5:1. Otherwise, the organic fluid cannot be fully vaporized and turned into a saturated vapor. These two constraints help to determine the maximum mass flow rate of the organic, namely, 47.5 kg/s. The mass flow rate of the minor stream of CO_2 is also 47.5kg/s, while that of CO_2 attending the power cycle is 237.5kg/s.

Since the 1+1=2 mode fails to produce more power than a pure CO_2 direct expansion model, our challenge lies in conjecturing a different approach to utilize the enthalpy contained in CO_2 returning from the geothermal reservoir. It worth noting that the organic vapor has to be condensed to liquid before its planned returning to the power cycle. And CO_2 expanding to a given lower pressure will always have a lower temperature during the expansion process. If one combines the expansion stages of two species together, the temperature drop of CO_2 may aid in the cooling and condensation of the organic vapor. So why not try to bring these two species together in the first place?

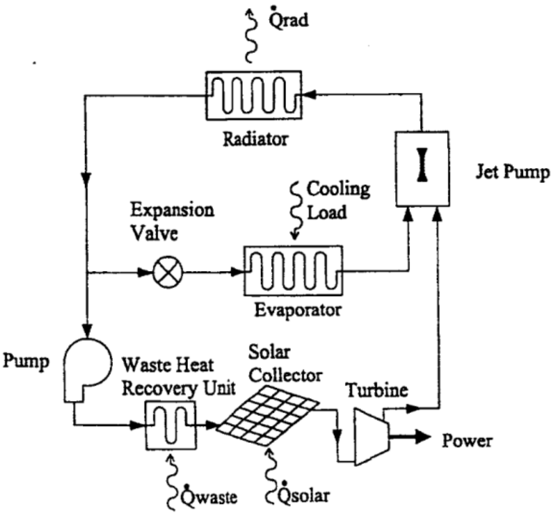

Figure 5- Schematic of the Solar Integrated Thermal Management and Power (SITMAP) Cycle utilizes jet pump to realize blending CO_2 and another working fluid at different pressure.

Thus, a special fluid mixing step aiming for blending fluids with different pressure were devised, similar to the Jet Pump in SITMAP system[6]. The CO_2 coming back from the production well has a much higher pressure than the saturated organic fluid. So some equally spacing, thin channels were placed within the mixer, where the organic working fluids is injected to the wall of the channels (the throat) due to lower pressure caused by narrowing the tubes and the speeding up of the CO_2. After their blending, the organic working fluid is boiled and turned into vapor, while the temperature and entropy of CO_2 are reduced at still much higher pressure. Then both of the species undergo the expansion stage. As for each step of the expansion, CO_2 cools down faster than the organic vapor does. Hence organic vapor acts like a temporary reservoir of thermal energy, by way of returning the thermal energy stored in vapor phase back to CO_2 as the quality of the vapor is becoming lower, while experiencing its own expansion. As the heat transfer between occurs within the expanders, more power output can be expected because the heat transfer from the organic vapor to CO_2 has the chance to be converted to mechanical work before it turns out to be useless as waste heat in turbine exhaust.

This is similar in hail stone weather that occurs usually in summer. In other seasons when the hot air rises, expansion and diffusion/advection to the surroundings eventually makes the air cooler, and thus the ascension movement stops at certain elevation. For countries in northern Hemisphere, summer represents the hottest months in a year, when more water content is contained in dry air. Such humid air always rises to higher elevation since the enthalpy of both dry air and the humidity combined is greater than that of the drier air. The air mostly becomes cooler when they stops, therefore leading to condensation and eventually the deposition of water into bulk ice.

The humid air situation is now replaced by CO_2 plus organic vapor. Let us quantify the energy input and output of this transcritical CO_2-ORC combined cycle. (323.15K, 9.6MPa) pure CO_2 ascending from the production well is blended directly at the ground surface with (313.15K, 1.3694MPa) saturated propane. After blending, the (9.6MPa 323.15K) drops to (9.6MPa, 314.99K), while the propane becomes (314K, 1.3694MPa) slightly superheated vapor. Then both species are sent to expander to generate mechanical work. 0.75

isentropic efficiency is assigned to both expansion stage. The final partial pressure at the outlet of the CO_2 expander is set to be 5MPa. Accordingly, the final partial pressure of the organic vapor is 1MPa. The thermodynamic state of CO_2 and propane can be decided respectively after the expansion, i.e., (287.43K, 5MPa) for the CO_2 in two-phase region and (301.39K, 1MPa) for the propane, which is still slightly superheated. It is obvious that if gaseous CO_2 and propane vapor are evenly mixed, the condensable propane vapor will transfer heat to the CO_2 and turn into liquid, till a thermodynamic equilibrium between the two species is reached. The (301.39K, 1MPa) vapor will firstly drop to (300.09K, 1MPa), before entering to a two phase region, and keep transferring heat to CO_2 until it is fully turned to liquid. When its own temperature reaches 287.43K, the heat transfer stops. It was found that (301.39K, 1MPa) vapor had turned to subcooled liquid of (287.43K, 1MPa), before CO_2 moved out of two phase region. So the total energy transferred from 1/5 kg propane to 1 kg CO2 is 73.744KJ. The value is significantly larger than energy separately produced from propane (1/5kg) and CO_2 (1kg) during expansion, which are 2.163KJ and 8.31KJ in respect. If only 30% of this stored energy is converted to work, mechanical energy output can be increased to 22.12KJ per kg CO_2 attending the main cycle.

However, condensation of CO_2 at 287.43K, two-phase region poses big problem for most regions on Earth if the power planet is supposed to run all the year round, plus that now the propane is sub-cooled liquid. Liquid CO_2 and propane may be soluble or slightly soluble at the current sate, causing problems to separate propane from CO_2. However if the two phase liquid-gas mixture is compressed to higher pressure, then condensation of CO_2 may become much easier. Our calculation shows that compression did work to the fluids, causing phase separation between CO_2 and propane. The propane will absorb heat during compression, but remains at subcooled liquid, while saturated CO_2 will turn into superheated gas.

With a compressor having isentropic efficiency of 0.8, CO_2 is compressed from 5MPa to 6MPa. The compression needs 6.66KJ energy to compress 1 kg CO_2, while lifting the temperature of CO_2 to 295.95K. Now 6MPa partial pressure for CO_2 indicates that partial pressure for the propane will become 1.2MPa, if saturated. But saturation temperature for 1.2MPa propane is 307.53K. If propane is in thermal equilibrium with CO_2 after compression, it is a sub-cooled liquid versus CO_2 being a superheated gas (its saturation temperature is 295.13K). In this fashion, CO_2 can be literally separated from propane.

If the 6MPa CO_2 is dumped immediately to the injection well, some but not all CO_2 can make their way back to the geothermal reservoir, depending on the average density of fluid in the production well. For the enhancement of tapping the geothermal energy, it is ideal to compress CO_2 to liquid or supercritical state. One can either compress the (295.95K, 6MPa) into 7.3MPa, with the same compressor and another 7.4KJ energy input for compressing 1 kg of CO_2. Or one can drill a vertical well, and compress CO_2 using its own gravity! The density of CO_2 (295.95K, 6MPa) is 203.98kg/m^3 while that of the CO_2 (310.15K, 7.3MPa) is 233.25kg/m^3. Using the change in pressure $\Delta p=\rho gh$, Compression of CO_2 to desired pressure (7.3MPa) requires depth of "cooling well" ranging from 568.14 m to 649.67 m. And heat pipe or heat pump running on propane can be used to recover the heat during compression. CO_2 is cooled at the downhole of this "cooling well" to slightly less than 303.67K, turning into liquid. In this case, at the cooler end of the heat pipe, propane is cooled to liquid at 303.15K, and pressure of propane is maintained slightly higher than 1.079MPa. Compression of liquid propane to 1.369MPa takes little energy and raise the temperature to 303.44K. At this point the cycle is completed.

Table 4 - Energy input and output for each component in the cycle for 1 kg CO_2 attending the cycle

Power output	(Isentropic)eff.	Energy output for 1kg CO_2
Power output from the CO2	75%	8.31 KJ
Power output from the organic vapor	75%	2.163 KJ
Power from heat transferred from the organic vapor to CO2	75%	73.744 KJ*30%=22.12 KJ
Sum	--	32.593 KJ
Power input	(Isentropic)eff.	Energy input for 1kg CO_2
Compression of CO2	80%	6.66 KJ
Compression of organic liquid	80%	0.75 KJ
Power estimated for total separation, dry cooling and moving both species around	--	3 kJ
Sum	--	10.41 KJ

Total energy carried by 1 kg of CO_2: 85.68 kJ/kg

Energy spent from 1 kg of CO_2 at the production well

1/6 kg CO_2	5/6 kg CO_2
Function: preheat the propane to saturated state, and return back to the reservoir after supplying geothermal heating to utilities.	Function: attend the power cycle blending with saturated liquid propane to boil it.

The total efficiency of the cycle:

$$\frac{(32.593 - 10.41)\text{KJ} \times 5/6}{85.68\text{KJ}} = 21.58\%$$

Total mass flow rate of CO_2 with no parasitic energy consumption: 285 kg/s

Mass flow rate of CO_2 for heating the organic: 47.5 kg/s

Mass flow rate of CO_2 attending the power generation cycle: 237.5 kg/s

Total power output of a CPG/EGS geothermal plant running on CO_2: 5.27 MW

Carnot efficiency of the power cycle (Considering turbine outlet and inlet, plus temperature of geothermal reservoir):

Inlet of the expanders: 323.15 K; outlet of the expander: 287.43 K.

$$\eta_{c-1} = 1 - \frac{T_2}{T_{1-1}} = 1 - \frac{287.43\text{K}}{323.15\text{K}} = 11.05\%$$

$$\eta_{c-2} = 1 - \frac{T_2}{T_{1-2}} = 1 - \frac{287.43\text{K}}{375.65\text{K}} = 23.48\%$$

The efficiency of the cycle is even much higher than Carnot cycle efficiency of the cycle. However, if the control volume to conduct thermodynamic calculation has included the geothermal reservoir, the Carnot efficiency can be as high as 23.48%. A detailed study on the properties of mixture and its expansion and compression process is required to quantify the percentage of heat transfer that can be converted to volumetric work. Larger the percentage heat transfer, the greater power output will be. Let us proceed to further discussion before discarding the seemingly erroneous result.

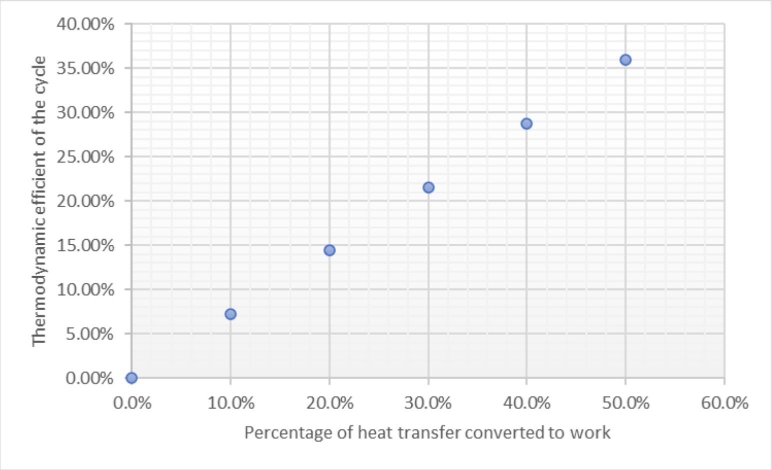

Figure 6: Total thermodynamic efficiency of the CO_2-ORC combined cycle as a function of the fraction of thermal energy transferred from the propane vapor to the CO_2

4. DISCUSSION

4.1 Why Carnot cycle is seemingly exceeded?

Thank to Kai Wang's input from the institute of refrigeration and cryogenics, Zhejiang University, who had mentioned the exergy destruction when fluids of different pressure are blended and become a homogeneous fluid. According to Sandia's report and Xinli Lu's results[7], the blending of supercritical CO_2 and propane may result in a homogeneous fluid, and even when a proper diffuser is devised after the mixer, the pressure cannot return back to their original value. If the partial pressure of CO_2 and propane is less than 9.6 MPa and 1.3694 MPa for the CO_2 and propane when expansion starts, the mutual thermal energy exchange may be less, which also pose limits to the maximum power output from the "internal" thermal energy exchange.

But even with exergy destruction, we are still confident at the effectiveness of the result. The majority of energy output from such low temperature thermodynamic cycle comes from an asymmetric process of boiling and condensation. No matter how much initial pressure head is lost during mixing stage, the organic vapor always absorbs heat at higher pressure, and release it when its pressure gets lower, thereby potentially giving off more thermal energy since the H_{fg} becomes greater at lower pressure.

According to our calculation so far, other working fluids, such as isobutane exhibits similar behavior like propane. Whereas fluids like R22, whose temperature drops faster at given partial pressure than CO_2, are not able to significantly increase the power output like the former candidates.

4.2 How the efficiency of the system is raised

From the above-conducted calculation, ORC coupled with CO_2 geo-cycle via a heat exchanger is less productive than the cycle with additional power output from the expansion of CO_2 itself. But such design layout do not have the advantage over the direct expansion system in principle, if the temperature of the CO_2 fluid at production wellhead is very low. It is only by combining the CO_2 direct expansion with ORC in a mixing device, that the power output can be theoretically uplifted.

According to Hugenroth and Wooyoung Kim's study[8][9], the alteration of adiabatic expansion to polytropic process reduces the polytropic index, thus can increase the power output from the expansion while reducing the power input to the compressor. It is found in our primary study that C_p/C_v is a large value, and the simultaneous existence of organic fluid does have the potential to reduce polytropic index, making it closer to 1, thereby generating more power using CO_2 and the organic fluid compared to that of a direct CO_2 expansion system.

4.3 How the calculation results help in designing the system in real circumstances

Since our research have not considered the pressure loss of both fluids, and property change of them, i.e., the critical point of CO2 and boiling point of them, it is important to consider the kinetic properties of both species when they are combined into a third fluid. It worth further exploration to consider how their behavior varies physically and chemically with our simple calculation model, hopefully with Aspen and pilot, small scale experimental system, to test the properties of fluids empirically. Even so, the pressure head loss can be compensated by a moderate compression stage, which may both lift the pressure of supercritical CO2 and liquid organic working fluid to higher pressure, thus compensating for the pressure loss they encountered during mixing and expansion stage. The approach may also improve the flexibility of the operation when applied to different geothermal sites both domestic and abroad. Likewise, more adaptable turbine design capable of withstanding mass fraction of liquid up to 17-20% needs to be implemented[10].

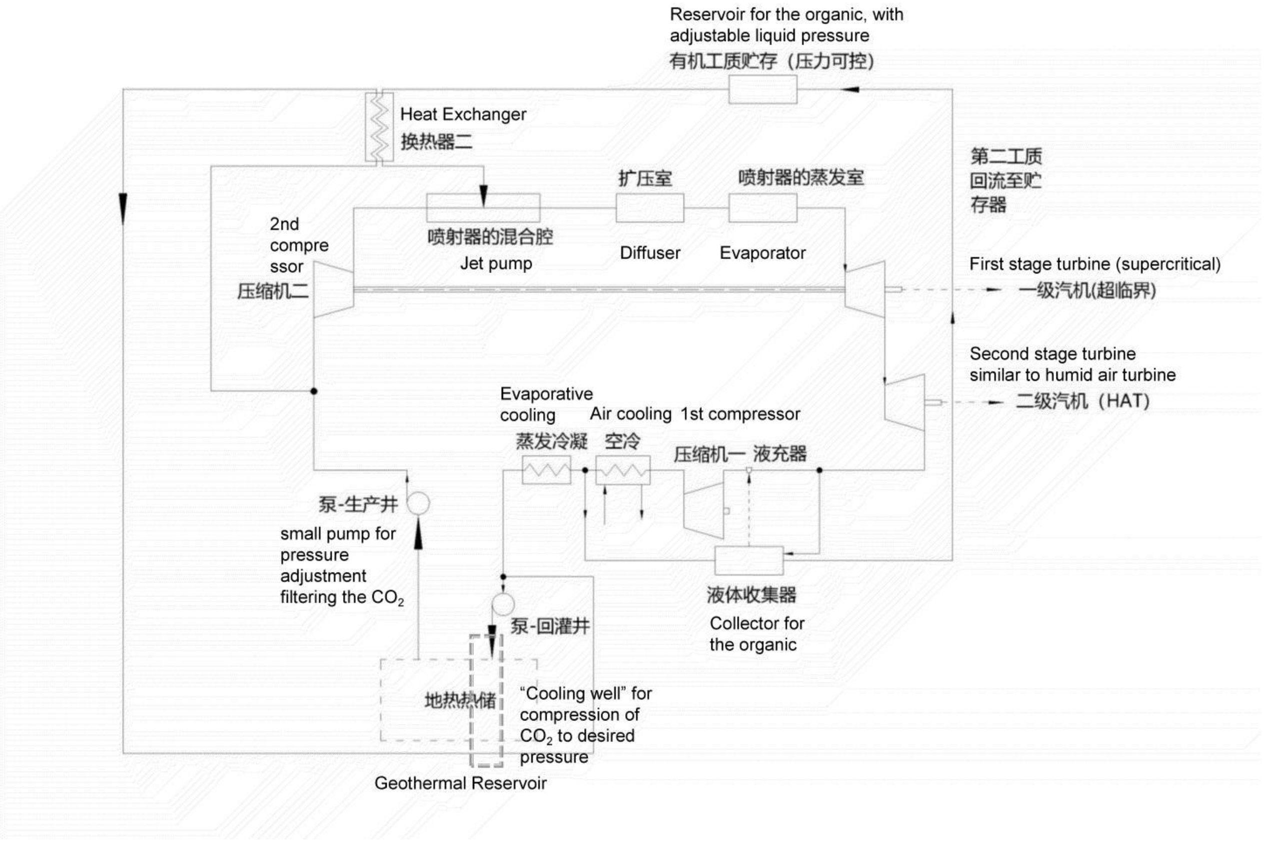

Figure 5- Schematic design of the CO_2-ORC combined cycle with compression added prior to entering the mixing chamber of a jet pump so as to moderately increase CO_2 pressure, making its pressure recoverable to the original pressure at the production wellhead.

4.4 Cooling and separation strategy: Evaporative vs drying cooling

It is still crucial to count on the importance of fluid separation: due to phase- equilibrium of organic vapor, a tiny fraction of organic vapor will still lost in superheated CO_2, a disadvantage of the economic liability of the system if the CO_2 will finally go back to naturally fractured reservoir or layers of sandstone found in CPG system. This explained the design approach we had to compress CO_2 from 6 MPa to 7.3 MPa by gravity: The perpendicular well about the length of 600 meters, leaves room for totally recycling the organic vapor by deposition of the vapor to the membrane module or other fabricated surface, combined with natural heat pipe design to return the fluid back to the plant on the ground with very little power consumption. Both drying cooling and evaporative cooling can be eligible to handle the task, since the dry air stream needs only to be less than 30 ℃. And this will be studied further with joint effort from other universities if situation allows.

5. CONCLUSION:

The very low temperature supercritical CO_2 at 9.6MPa, 50℃ is still capable of power generation, if a proper design of transcritical-ORC combined cycle utilizing fluids' mixture is carefully made. Such design is a novel modification to the direct expansion system of CO_2 based geothermal power plant, making it adaptable to simultaneous sequestration of carbon.

The major power output comes from the latent heat stored in the vapor of an organic species. 30% of heat transfer between two species converted to work can lift the efficiency of the cycle close to Carnot efficiency. 20% conversion of the heat transferred raises the efficiency close to 15%. Even 10% conversion of heat transferred to work renders the system superior than the best direct expansion system. It also produces significantly more power than conventional ORC, since both CO_2 and the organic fluid attending the power generation create a 1+1>2 scenario.

Empirical experiments and simultaneous simulation are required in future regarding the properties of blended fluid after mixing. Effectiveness of the design relies largely upon the thermodynamic properties of the fluid mixture, and how much of the to-and-fro heat transfer can be converted to work-a major accent of future study.

Fluids such as isobutane and propane can produce steam that transfers heat to CO_2 during its simultaneous expansion. but not fluids like R22 having greater temperature descending range than CO_2. Exergy destruction during fluid mixing at different pressure and temperature can be compensated by compression prior to entering the jet pump. Thermosiphon effect that occurs on large scale geothermal system is crucial for the success of the power cycle, not just in circulation and heat mining, but also in compression and condensation of CO_2. Thus higher thermal efficiency, more electricity and freedom of using CO_2 as the direct heat transmission fluid for large scale deep geothermal reservoir can be achieved with the power cycle. Such mode favors the utilization of geothermal energy to reduce the cost of CO_2 capture, utilization and geological storage(CCUS), while offering new insights about how CO_2 can be utilized in large quantity.

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