Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Options to Use Solar Heat to Enhance Geothermal Power Plant Performance

Hal Gurgenci

School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, QLD 4072, Australia

h.gurgenci@uq.edu.au

Keywords: Power generation; solar hybrid; air-cooled condensers.

ABSTRACT

Many future geothermal plant locations are located in dry regions of the world. This is especially true for future EGS (Enhanced Geothermal Systems) locations.

These are areas also blessed with high levels of solar incidence. The solar heat can be captured at different temperatures using different solar collector technologies. This makes it possible to consider a number of scenarios in which solar heat can be used to boost the geothermal plant performance.

The Queensland Geothermal Energy Centre of Excellence (QGECE) of the University of Queensland is investigating some of the most promising methods in which solar and geothermal heat can be combined. Most of these methods have been considered with a focus on future EGS plants but they may also be applicable to more conventional geothermal applications. The combination amounts more than the sums of the individual components in this instance.

The paper will describe how solar and geothermal heat can be combined to generate more value than what can be generated by each source individually.

The applications will include the following: boosting geothermal fluid temperatures to increase cycle conversion efficiencies; enhancing the performance of natural draft dry cooling towers by using solar heat; and solar chilling of future supercritical CO2 EGS plants to maintain higher efficiencies.

1. INTRODUCTION

There are three main possibilities in which solar heat can be used to help the performance of a geothermal power plant: boost the temperature of the geothermal fluid before it enters the plant; further boost the binary cycle fluid temperature after it is heated by the geothermal fluid first; and help the air-cooled condenser performance to boost the cycle efficiency.

The first two options increase the power plant efficiency by increasing the turbine inlet temperature. The last option increases the power plant efficiency by reducing the turbine outlet pressure.

Mathur(1979) assessed the feasibility of solar geothermal hybrids for flash geothermal plants where solar energy was used to increase the enthalpy of the geothermal fluid. They found that the hybrid plant produced electricity cheaper than a solar-only plant but more expensive than a geothermal-only plant. There has not been much attention given to solar+geothermal hybrids since then. In more recent years, Lentz and Almanza[9, 10] proposed using solar power from parabolic trough concentrators to increase the steam flow from geothermal wells. The proposal was to produce steam by running the water from the cooling tower through the collector field and to inject the steam into the fluid coming from the well to increase its enthalpy.

There has not been serious consideration given to hybrids in binary plants. The vast majority of the binary geothermal plants are based on Rankine cycles using an organic fluid or steam depending on the resource temperature (Di Pippo, 2009).

It is difficult to make solar boosting economically feasible with a Rankine-cycle plant. This is because most of the heat added to the Rankine cycle is latent heat at the saturation temperature corresponding to the turbine design inlet pressure. It is not possible to significantly shift this temperature upwards without changing the turbine inlet pressure. Changing the pressure requires a separate turbine. Therefore, solar boosting of a geothermal plant based on a Rankine cycle requires two turbines: one for geothermal-only operation and the other for geothermal + solar. While such turbines exist, the optimum operating point would be elusive because of variable solar incidence and the inability of the plant to optimally track such variations.

Solar and geothermal heat can be combined without affecting the turbine inlet pressure if the heat transfer occurs on a gliding temperature line. A gliding-temperature cycle is one in which the heat addition and the heat removal occur over varying temperatures rather than at fixed evaporation and condensation points. An ammonia-water cycle is a gliding-temperature cycle (Kalina, 1982) and so are other mixed fluid cycles recently proposed, e.g. Angelino(1998), Colonna(2003), Chen(2011), This paper will consider solar-geothermal hybrids using supercritical and transcritical cycles.

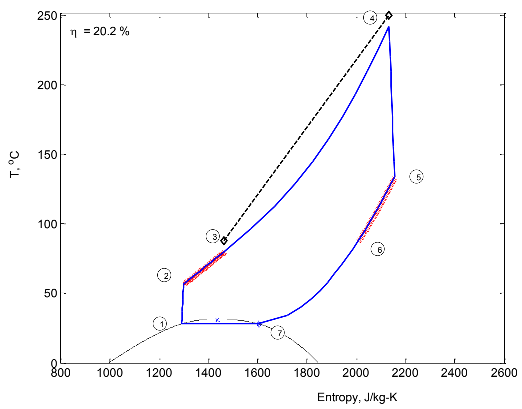
Zhang and Lior (2006), Zhang et al(2006) and Cayer et al(2009) proposed the use of supercritical CO_2 cycles with waste heat and similar resources at the same temperature range as a high-grade EGS resource, i.e. about 250 ^oC. The comparative benefits of these cycles are even more pronounced for geothermal applications, where a very important figure of merit is the power production from a given subsurface investment. Gurgenci et al(2006) and Atrens et al(2009,2010,2011) combined the concept of a supercritical CO_2 cycle with a supercritical CO2 geothermal reservoir as proposed by Brown (2000). In a supercritical geothermal CO2 siphon plant, the supercritical fluid is sent into the reservoir, extracts the heat and rises to the surface to turn a turbine. There are significant benefits on offer from the implementation of such a cycle but it requires further research to resolve issues concerning the interaction of CO_2 with the reservoir rocks and reservoir water

In an application of a supercritical cycle in an otherwise conventional binary plant configuration, the cycle fluid temperature tracks the brine temperature during the heat exchange process and, compared to an evaporating cycle where phase change occurs at a constant temperature, more of the brine heat is transferred to the cycle fluid. For a binary plant operating on a typical high-grade geothermal resource, one should expect a transcritical CO_2 cycle to provide a higher efficiency and a substantially higher plant output.

It is demonstrated further below in this paper that compared to a steam plant operating on the same high-grade geothermal resource, a transcritical CO_2 plant (supercritical turbine inlet and subcritical condenser pressure) would enjoy much higher generation levels at low ambient temperatures but the plant output would drop disproportionately as the ambient temperature rises. This paper proposes the use of solar energy to help an air-cooled transcritical CO_2 plant perform at its design-point performance through the year.

2. TRANSCRITICAL BINARY PLANT PERFORMANCE WITHOUT SOLAR BOOSTING

The performance of a transcritical CO_2 cycle is compared against a conventional steam Rankine plant option for a geothermal brine stream at a temperature of 250 ^oC and for a total brine flow rate of 500 kg/s. For a design-point ambient temperature of 20 ^oC, the power generation from the transcritical CO_2 plant would be 70 MWe at an efficiency of 20.2%. The cycle conditions at the design point are plotted on temperature-entropy coordinates in Figure 1a. The numbers in circles refer to positions in Figure 1b. As depicted in Figure 1b, the working fluid is heated to the saturation temperature in the preheeater (PRE) and is evaporated in the evaporator (EVA); it expands and generates power by turning a turbine (TUR); it condenses(CON) back to the liquid state; and then is pumped (P) to the evaporator pressure to repeat the cycle. The lines with crosses (2-3 and 5-6) in Figure 1a represent the recuperator. The stand-alone dashed line shows the brine cooling in the heat exchanger while the CO_2 is being heated from 3 to 4.



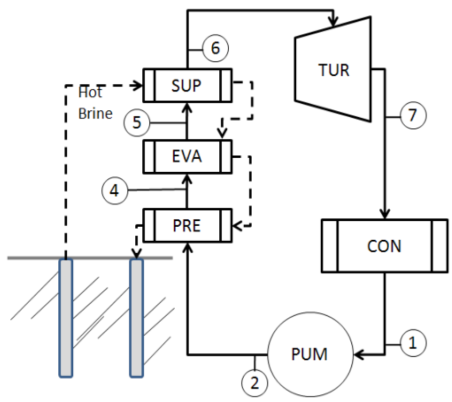


Figure 1a: Transcritical CO_2 cycle design performance

Figure 1b: Transcritical CO_2 power plant lay-out

Although transcritical CO2 cycles were proposed first for solar and waste heat recovery applications, their relative advantages are more pronounced for geothermal power plants. In a binary geothermal plant the heating medium is not an isothermal source but a hot brine stream that cools as it gives its heat to the cycle fluid. Therefore, the ideal cycle for a geothermal power plant is not the Carnot cycle but the so-called tri-lateral cycle, e.g. see Smith(1993) and Di Pippo(2009). Gliding temperature cycles such as a supercritical cycle approximate the ideal cycle better than the Rankine cycles.

In comparison with the CO2 plant in Figure 1a, the best design-point performance that can be obtained from a steam Rankine plant is plotted in Figure 2. To compare plants of the same complexity, this is for a single turbine and a real application would have slightly higher efficiency with slightly higher efficiencies.

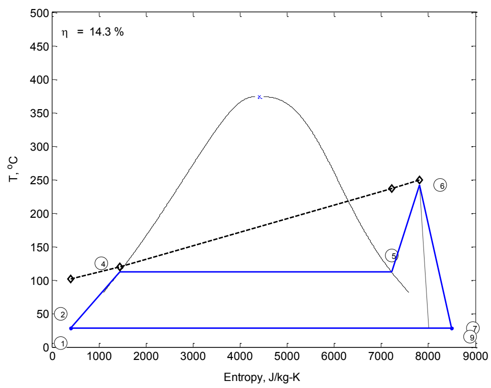


Figure 2: Design-point performance of the steam cycle for the same geothermal fluid conditions as for Figure 1a.

Operating on the same geothermal stream and at the same ambient temperature, the transcritical CO2 plant at the design point is predicted to produce 70 MWe of electricity at an efficiency of 20.2% and the steam Rankine plant is predicted to produce 45 MWe at an efficiency of 14.3%. The difference in power generation levels is more than what can be explained by the efficiencies alone. The transcritical plant produces more power by extracting more heat from brine because the supercritical fluid can track the brine temperature during the heat exchange process.

However, the design-point advantage of the transcritical CO_2 cycle disappears very quickly at higher ambient temperatures for an air-cooled plant. The performance drop at higher ambient temperatures is much more severe for the transcritical CO_2 cycle because the CO_2 compressor power consumption grows very rapidly at temperatures above the critical point. Figure 3 plots the simulated monthly power generation (in GWh) over the year for both transcritical CO_2 and steam Rankine cycles. The yearly total is 397 GWh for the steam Rankine plant and 428 GWh for the transcritical CO_2 plant.

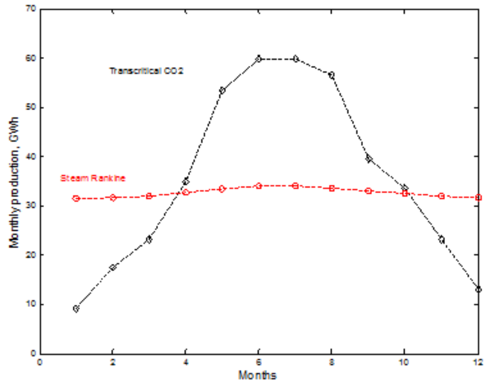


Figure 3: Monthly Electricity Generation by transcritical CO2 and steam Rankine cycles simulated for a typical Australian outback town

It is clear that while the design-point performance for the transcritical CO2 cycle is far superior, its off-design performance is very poor. To make it even worse, most of its generation occurs during the night when the ambient air is coolest and the electricity demand is at its lowest. The output from a transcritical CO2 plant is the lowest when the temperatures are the highest, which generally coincide with the peak grid demand. Peak demand conditions typically attract highest electricity spot prices.

Compared to the CO2 cycle, the steam Rankine plant is predicted to have a reasonably steady output through the year and while its output would diminish on hot days, the predicted reduction from the hottest to coldest ambient temperature is only 14%.

3. TRANSCRITICAL CO_2 PLANT WITH SOLAR COOLING

Past discussion on geothermal solar hybrid plants have been limited to boosting the geothermal fluid enthalpy by additional heating using a solar collector fluid. With a transcritical CO_2 plant, a more interesting possibility is offered by solar chilling. Since the performance degradation is caused by the CO_2 temperatures getting above the critical point due to insufficient cooling and since the degradation is severe even at small temperature elevations above the critical point, a relatively small amount of additional cooling capacity supplementing air cooling makes a significant difference. Since the maximum need for cooling coincides with the peak solar conditions, it makes sense to explore if the performance can be boosted by using solar input. Advances in sorption chilling technology, e.g. Kim and Ferreira(2008) and Desideri et al(2009), make this a serious proposition.

The predicted performance with the addition of solar cooling is added to the previous simulations in Figure 4. The drop in the performance in summer months is because no solar cooling is possible in summer nights and production stops when the air temperature is above 22^{o}C.

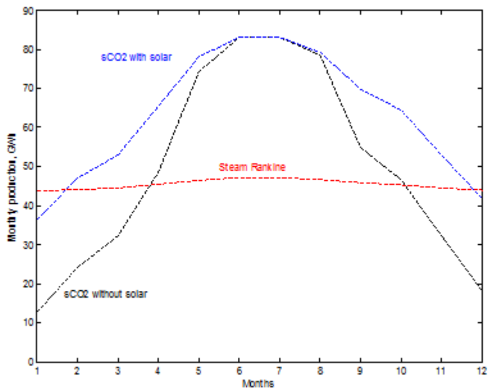


Figure 4: Monthly Electricity Generation by transcritical CO_2 with and without solar contribution and steam Rankine cycles simulated for a typical Australian outback town

The design of the solar refrigeration plant is beyond the scope of this paper. It is assumed that an evacuated tube collector field is used to provide fluid temperatures at about 150 ^{o}C at collection efficiency of 50%. Kim and Ferreira(2008) suggest coefficients of performance of about 0.8-1.2 at these collection temperatures providing solar thermal refrigeration at a cost of about 600-900 €/kWth or AUD $1000-1600/kWth for small- to medium-scale refrigeration applications.

The solar refrigeration system is designed to provide the design point performance on the hottest day of the year. This means the solar potential is underutilised at other ambient temperatures. The case study CO_2 plant parameters are listed in Table 1.

Table 1. Comparing steam and CO2 power plants with and without solar boosting for the latter

Brine temperature	250 ^{o}C
Brine supply	500 kg/s
Design-point air temperature	20 ^{o}C
Steam Rankine Plant	
Design-point power generation	45 MW
Design-point thermal efficiency	14.3%
Annual electricity generation	397 GWh
Brine heat exchanger UA	7934 kW/^{o}C
Transcritical CO_2 plant	
Design-point power generation	70 MW
Design-point thermal efficiency	20.2%
Brine heat exchanger UA	43524 kW/^{o}C
Geothermal only operation	
Annual total heat extraction from brine	2060 GWh
Annual air cooling total	1632 GWh
Annual electricity generation	428 GWh
Geothermal boosted by solar refrigeration	
Annual total heat extraction from brine	2650 GWh
Annual air cooling total	1853 GWh
Annual heat removal by solar refrigeration	250 GWh
Annual electricity generation	547 GWh
Solar collector area	231314 m^2
Solar collection efficiency (assumed)	0.50
Solar refrigeration thermal coefficient of performance (assumed)	1.0

As seen in Table 1, an additional 119 GWh of electricity is made possible from the same CO2 plant by using 250 GWh of solar heat collected from a collector field of 231314 m2 powering an appropriately-sized sorption chilling facility. This amount should be compared against the solar electricity that could have been generated from the same amount of solar heat driving a separate solar thermal plant. Assuming a solar collection fluid temperature of 150^{o}C that can be achieved with an evacuated-tube collector field, an air-cooled organic Rankine cycle using isopentane operating between 142^{o}C and 28^{o}C would achieve an efficiency of 18%. At this efficiency, 250 GWh of solar heat could produce 45 GWh of electricity. In comparison, using it to condense the CO2 when needed, at a chiller coefficient of performance of 1.0, the same solar collector field enables 119 GWh of electricity.

The extra electricity from solar boosting comes at an extra investment in the solar collector field and the solar chilling plant. The cost issues have not been addressed in this study. However, the important point to be made is that using solar heat to boost the performance of a geothermal plant under certain circumstances could be a better usage of the solar energy compared to using directly in its own standalone solar thermal power conversion plant. This is because the extra electricity generated by using the solar collectors to refrigerate the CO2 condensers is substantially higher than what would have been generated if the same collectors were used to power a separate standalone solar thermal power conversion cycle. We will define the ratio between the two as the solar amplification ratio, SAR. In other words,

$$SAR = \frac{MWH_{solaronly}}{MWH_{geo+solar} - MWH_{geoonly}} \quad (1)$$

where $MWH_{solaronly}$ is the electricity in annual megawatt-hours that would be generated from a standalone solar thermal plant by direct conversion of the solar heat to electricity through an ORC plant with based on an isopentane cycle; $MWH_{geoonly}$ is the electricity in annual megawatt-hours that would be generated from a CO_2 plant without solar boosting; and $MWH_{geo+solar}$ is the electricity in annual megawatt-hours that will be generated from the same geothermal plant with the addition of the solar chilling to keep it at its design-point performance even on the hottest day of the year. For the case study considered in this study, the value of SAR was 2.6.

3. SOLAR ENHANCED NATURAL DRAFT DRY COOLING TOWERS

The previous sections considered the use of solar boosting combined with new cycle technology, i.e. transcritical CO_2 cycles. The use of solar boosting may also make a significant performance to the air-cooled condenser performance in existing plant configurations. Zhou et al (2012, 2013, 2014) proposed a novel natural draft dry cooling tower concept where solar heating is used to boost the tower draft and hence the air-cooled condenser performance. As seen in Figure 5, a solar enhanced natural draft dry cooling tower (SENDDCT) would enhance the performance of a conventional natural draft dry cooling tower (NDDCT) by adding solar heat after the heat exchangers. The extra heating increases the buoyancy of the air inside the tower and helps to drive more air through the heat exchangers. The improved heat transfer rates caused by the higher air flow rates can be exploited to build a cooling system with either less heat exchanger areas or smaller towers resulting in a reduced capital cost in either case.

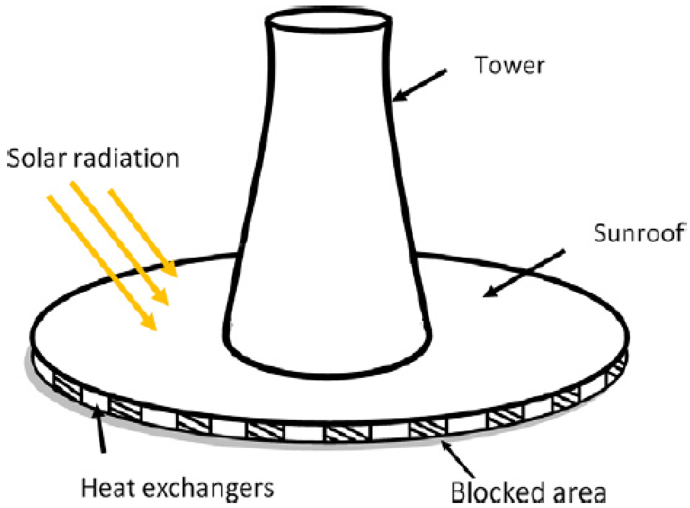


Figure 5: Configuration of solar enhanced natural draft dry cooling tower

Such a hybrid system as shown in Figure 5 would be particularly suitable for geothermal power generation. Compared to fossil-fired power generators, geothermal power plants require much larger heat rejection systems due to their relatively low efficiencies. A typical coal-fired power plant would require rejecting about 2 MW of heat for every MW of electricity it generates. A geothermal binary plant at half the efficiency of a coal-fired power plant would require rejecting about 5 MW of heat for each MW of electricity it generates; and it would get increasingly worse for lower-enthalpy geothermal resources at lower cycle efficiencies. Moreover, most geothermal power generation sites are located in arid areas where water is scarce and air cooling is the only option. Such sites feature at the same time high ambient temperatures leading to high parasitic losses when using fan-driven cooling systems. Preliminary results reported by Zou et al (2012, 2013, 2014) indicate that with the help of solar energy in conventional natural draft dry cooling system, the required tower height for a natural draft dry cooling tower can be reduced significantly. An alternative way of exploiting the extra benefits potential on cost enabled by solar heating would be by reducing the heat exchanger area while keeping the tower height the same. Either option leads to cost reduction above the additional cost of the solar collector field.

3. CONCLUSIONS

With the expected expansion of the EGS sector, there will arguably be many more binary geothermal power plants in the future. Such plants operating in dry climates need to be air-cooled and therefore suffer losses in their output at high ambient temperatures. Moreover, a significant fraction of the EGS resources being targeted have temperatures in mid-200 ^{o}Cs. At these temperatures steam is presently the only available option although this is not the optimum operating temperature range for steam turbines. Transcritical CO2 cycles deliver higher efficiencies and much higher outputs for such high-grade geothermal resources but unfortunately, compared to a steam cycle, they are more vulnerable to high ambient temperatures.

In this paper, a solar absorption chilling option is proposed to enhance the performance of an air-cooled transcritical CO_2 cycle powered by a typical HFR (Hot Fractured Rock) geothermal resource. The results are compared against those that would be obtained using a steam cycle. Both the CO_2 and the steam plants are influenced by the ambient air temperatures. While the design-point power generation for the CO_2 plant is 55% higher than the steam Rankine alternative, the simulated annual electricity production results for the two plants are much closer, with the CO_2 plant generating a marginally higher amount of electricity in a given year. This is because the CO_2 cycle is much more vulnerable to changes in the ambient temperature and the simulated performance of a CO_2 plant drops sharply with increasing ambient temperature. The drop is not as pronounced with the steam cycle. The overall viability of a CO_2 plant is however substantially improved by using solar heat. The best use of solar heat is in providing extra cooling for the CO_2 condensers in addition to an initial stage of air cooling. With such an arrangement, the design point of a CO2 plant is maintained through the year, except during hot summer nights. This is a good use of the solar heat because the additional amount of electricity produced from the chilled CO_2 plant is 2.6 times higher than the electricity that could be produced from a separate power plant powered by the same solar heat.

Another option to use solar heat to boost the geothermal plant efficiencies by boosting the air-cooled condenser performance is by using a solar enhanced natural draft dry cooling tower. It has been shown that the use of a solar collecting skirt around a natural draft dry cooling tower with the finned-tube heat exchanger panels placed around the perimeter of the solar collector provides a significant improvement of the plant performance.

REFERENCES

Atrens, A.D., Gurgenci, H., Rudolph, V.: CO_2 thermosiphon for competitive geothermal power generation. *Energy & Fuels*, **23**:553-7 (2009).

Atrens, A.D., Gurgenci, H., Rudolph, V.: Electricity generation using a CO_2 thermosiphon, *Geothermics*, **39:**161-169(2010).

Atrens, A.D., Gurgenci, H., Rudolph, V.: Economic Optimisation of a CO2-based EGS Plant. *Energy & Fuels*, **25**(8):3765–3775 (2011).

Angelino, G. and Colonnadipaliano, P.: Multicomponent Working Fluids For Organic Rankine Cycles (ORCs). *Energy*, **23**(6): 449-463 (1998).

Brown, D. W.: A Hot Dry Rock geothermal energy concept utilizing supercritical CO_2 instead of water. 25[th] Workshop on Geothermal Reservoir Engineering, Stanford (2000).

Cayer, E., Galanis, N., Desilets, M., Nesreddine, H., and Roy, P.: Analysis of a carbon dioxide transcritical power cycle using a low temperature source. *Applied Energy*, **86**:1055-63 (2009).

Chen, H., et al.: A supercritical Rankine cycle using zeotropic mixture working fluids for the conversion of low-grade heat into power. *Energy*, **36**(1):549-555 (2011).

Colonna, P. and Silva, P.: Dense Gas Thermodynamic Properties of Single and Multicomponent Fluids for Fluid Dynamics Simulations. *Journal of Fluids Engineering*, **125**(3): 414 (2003)

Desideri, U., Proietti, S., and Sdringola, P.: Solar-power cooling systems: Technical and economic analysis on industrial refrigeration and air-conditioning applications. *Applied Energy*, **86**:1378-86 (2009).

Di Pippo J.: Ideal efficiency for geothermal binary plants. *Geothermics*, **36**:276-85 (2009).

Gurgenci, H., Rudolph, V., Saha, T., Lu,, M.: Challenges for geothermal energy utilisation. 33[rd] Workshop on Geothermal Reservoir Engineering, Stanford (2008).

Kalina, A.I.: Generation of energy by means of a working fluid, and regeneration of a working fluid. US Patent 4,346,561 (1982).

Kim, D.S., and Ferreira C. A. I.: Solar refrigeration options – a state-of-the-art review. *Int J of Refrigeration*, **31**:3-15 (2008).

Lentz, A., and Almanza R.: Solar-geothermal hybrid system. *Applied Thermal Engineering*, **26**:1537-4 (2006).

Lentz, A., and Almanza R.: Parabolic troughs to increase the geothermal wells flow enthalpy. *Solar Energy*, **80**:1290-5 (2006).

Mathur, P.N.:An assessment of solar geothermal hybrid system concepts. US Department of Energy, Report SAN-1101-14/1(1979).

Smith, IK. Development of the trilateral flash cycle system. Part 1: Fundamental considerations. *Proc. Inst. Mech. Eng. Part A*, **207**:179-94 (1993).

Zhang, N., Lior, N.: A novel near-zero CO2 emission thermal cycle with LNG cryogenic exergy utilization. *Energy*, **31**:1666-79 (2006).

Zhang, X.R., Yamaguchi, H,, Fujima, K., Enomoto, M., and Sawada, N.: Study of solar energy powered transcritical cycle using supercritical carbon dioxide. *Int J Energy Res*, **30**:1117-29 (2006).

Zou, Z., Guan, Z., Gurgenci, H., and Lu, Y.: Solar enhanced natural draft dry cooling tower for geothermal power applications. *Solar Energy*, 86:2686-2694 (2012).

Zou, Z., Guan, Z., and Gurgenci, H.: Optimization design of solar enhanced natural draft dry cooling tower. *Energy Conversion and management*, **76**:945-955 (2013).

Zou, Z., Guan, Z., Gurgenci, H.: Numerical simulation of solar enhanced natural draft dry cooling tower. *Solar Energy*, 101:8-18 (2014).