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Integrated Research on Hot Dry Rock Power Generation and Heat Extraction with Utilization of an Increasing-Pressure Endothermic Power Cycle (IPEPC)

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ABSTRACT

In this study, a closed-loop geothermal system (CLGS) using downhole heat exchanger (DHE) was proposed to extract heat from the HDR resources in order to avoid the problems associated with the current EGS technology. An increasing-pressure endothermic power cycle (IPEPC), with an increasing-pressure endothermic process in the DHE and CO_2-based mixture as working fluid, has been developed for the geothermal wells with depths ranging from 2 km to 4 km. The mixture types and mass ratio of the working fluid, and the operation parameters of the IPEPC have been optimized simultaneously. The power generation performance of the IPEPC has been compared with that of organic Rankine cycle (ORC) and that of flash-steam system under the same geothermal conditions. When the DHE length (*L*) is 2000 m, the net power output of the IPEPC is 17.5%, 98.4% and 120% higher than that of the t-CO_2, SF and ORC respectively; whereas it is only 7.4%, 9.1% and 21.7% if the *L* is 3000 m. Results obtained in this study are of engineering guiding significance for hot dry rock power generation.

Keywords: Integrated research, Power generation, Heat extraction, Increasing-Pressure Endothermic process, CO_2-based mixtures

NONMENCLATURE

Abbreviations	
HDR	Hot Dry Rock
EGS	Enhanced Geothermal System
ORC	Organic Rankine Cycle
SF	Single-flash system
IPEPC	Increasing-Pressure Endothermic Power Cycle
t-CO_2	Trans-critical CO_2 Cycle
DHE	Downhole heat exchanger
L	DHE length

1. INTRODUCTION

The rising population along with a growing reliance on modern technology has increased energy demand. In the past few decades, studies have indicated that utilizing geothermal energy as well as enhancing the efficiency of geothermal systems currently being used are both viable choices for addressing these challenges [1]. Geothermal energy is thermal energy which is generated and stored within the Earth. Geothermal energy is a clean, renewable resource that can be tapped by many countries around the world located in geologically favorable places. At the end of 2021, the capacity for geothermal electricity production throughout the world was 15854 MW [2].

The global geothermal resources can be divided into five categories: hydrothermal, dry steam, hot dry rock (HDR), abnormal geopressured, and magma resources, among which the first three resources have been widely studied [3]. Investigation shows more than 90% of the total US geothermal resource is stored in HDR. Aiming to extract the energy stored in HDR, the prototype of an Enhanced Geothermal System (EGS) was designed and implemented by the Los Alamos National Laboratory in the 1970s [4]. The traditional EGS is straightforward: Creating an artificial reservoir by hydraulic stimulation; Connecting injection and production well by circulating water, and then heat can be extracted from the rock. Some practical issues also exist in the EGS application, such as corrosion and scaling in wellbores and power plant components, water contamination, seismic-induced risk, and the loss of working fluid while circulating [5,6]. In order to avoid the problems

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associated with the current EGS technology, seek a reliable and long-lasting heat extracting system and a novel power cycle is the key to effective utilization of hot dry rock resources.

A numerical study was also carried out to evaluate the heat transfer performance of CO_2 for EGS applications [7]. It was found that CO_2 had a better heat transfer performance than H_2O in terms of its heat extraction rate. Son et al. [8] carried out a simulation that compared the critical parameters that affected the heat transfer performance of CO_2 and water; they concluded that CO_2 was suitable for geothermal reservoirs with lower temperatures below 150°C. The power generation of four CPG (CO_2 plume geothermal) systems and two brine-based geothermal systems have been compared by Adams et al. [9], the results shows that the CPG direct geothermal system obtained the highest net power output. It is also worth noting that CO_2 has a fairly low critical temperature (about 31.2°C); hence, it is impossible to condense the pure CO_2 by cooling-water under ambient temperature.

In this study, a closed-loop geothermal system (CLGS) using downhole heat exchanger (DHE) was proposed to extract heat from the HDR resources in order to address the challenges associated with artificial fracturing-based EGSs. The CO_2-based mixture working fluid has a higher critical temperature than CO_2, which allowed us to still use a conventional condenser [10]. In addition, the CO_2-based mixture has an obvious buoyancy-driven thermosiphon effect under the impact of gravitational potential energy, results in a higher DHE outlet pressure than inlet pressure [11].

An increasing-pressure endothermic power cycle (IPEPC), with an increasing-pressure endothermic process in the DHE and CO_2-based mixture as working fluid, has been developed for geothermal power generation in this article.

2. SYSTEM DESCRIPTION

The schematic of the Increasing-Pressure Endothermic Power Cycle (IPEPC) and the temperature-entropy (T-S) diagram of the power generation system are shown in Fig. 1a and 1b respectively. The IPEPC is consisted of downhole heat exchanger (DHE), turbine, generator, condenser and pump.

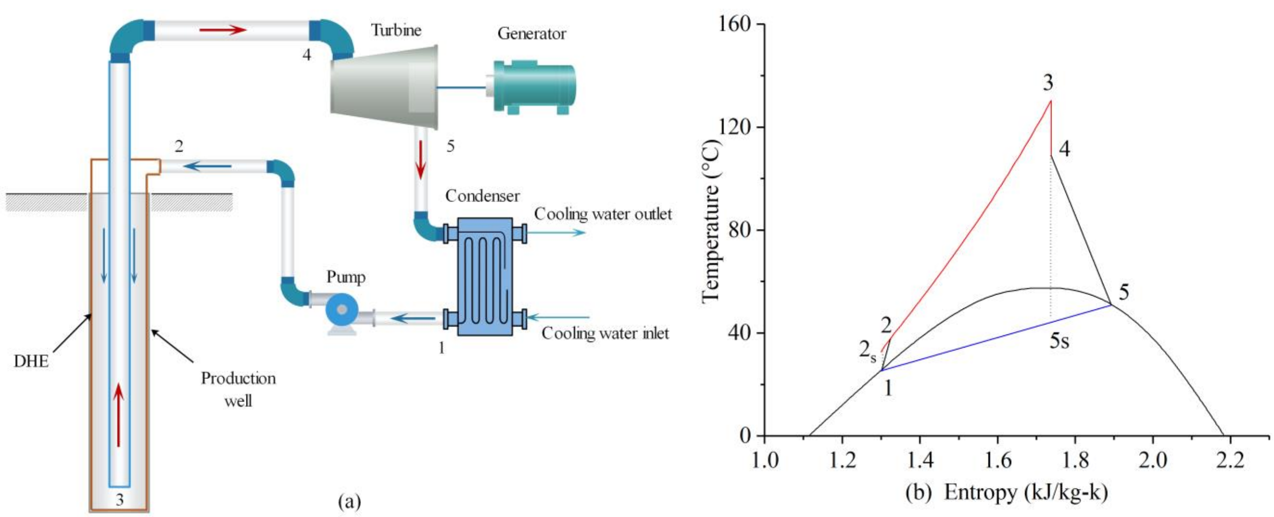

Fig. 1. Schematic and Temperature-entropy diagrams of the Increasing-pressure endothermic power cycle (IPEPC)

The liquid working fluid (CO_2-based mixture) from the condenser is pressurized into supercritical state (process 1-2) and is then injected into the DHE annular region of outer tube. The downward annulus flow absorbs heat from the rock, as the Fig.1b process 2-3 shown. The inner and outer pipes of the DHE are connected in the bottom area. The working fluid passes upward from the bottom to the top (process 3-4) in the inner pipe, which is a decreasing-pressure and -temperature process. The working fluid from DHE enters the turbine to drive the generator for electricity generation (process 4-5). The turbine exhaust (state 5) flows into the condenser where it is condensed into complete saturated liquid (state 1), then another cycle.

The process 2-4 is an Increasing-Pressure Endothermic process, which is differ from the heat absorption of working fluid in traditional ORC system. Due to the difference in working fluid density between the upward and downward tubes, the buoyancy-driven thermosiphon effect in the DHE can boost the working-fluid's DHE outlet pressure. Hence, the IPEPC power generation performance can be improved.

3. RESULTS AND DISCUSSION

Fig.2 shows the effects of different CO2-based mixture and mass flowrates (m_m) on the DHE outlet pressure (p_{out}) and IPEPC net power output (W_{net}). The DHE length (L) and inlet pressure (p_{in}) are maintained as 3000 m and 12 MPa respectively.

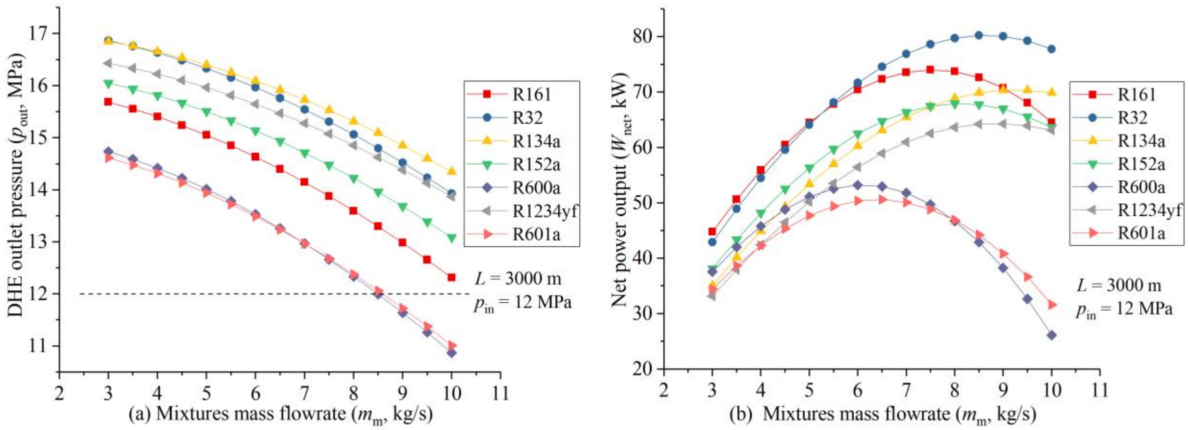

Fig. 2. Effects of the working fluid flowrates on DHE outlet pressures and IPEPC net power output with respect to different CO_2-based mixture (CO_2-R32 = 0.5-0.5)

In Fig.2a, the general trend is that the DHE working fluid outlet pressure (p_{out}) of each working fluid decreases with an increase of its mass flowrate m_m. CO_2-R134a has the highest p_{out} among the seven CO_2-based mixture working fluids. CO_2-R32 has the second highest p_{out}, CO_2-R601a and CO_2-R600a are the two working fluids showing the lowest p_{out}.

The horizontal black-dash-dotted line denotes the working fluid inlet pressure (p_{in}). Pressure variations of a p_{out} above this line indicates there exists a thermal siphon effect, which means, by use of gravitational potential energy, the p_{out} of the DHE can be greater than the corresponding p_{in} of the DHE for a certain range of mass flowrate m_m. Since the thermal siphon effect can compensate pump power consumption ($p_{out} > p_{in}$), the inlet pressure of the turbine becomes higher and hence result in a better power-cycle performance.

Fig.2b shows the IPEPC net power output (W_{net}) variations with respect to different mm amd CO_2-based mixtures, under the condition: L = 3 km. Each mixture has an optimal m_m that maximizes the W_{net}. Using CO_2-R32 as working fluid has the highest W_{net} (80.3 kW for m_m = 8.5 kg/s), slightly higher than using CO_2-R161 as working fluid (73.2 kW for m_m = 7.5 kg/s);.

Fig.3 shows the effect of mass flowrate (m_m) and DHE inlet pressure (p_{in}) on the IPEPC W_{net}, with the DHE length (L) maintained at 3000 m. The optimal mass flowrates are almost unaffected by p_{in}, all around 9 kg/s. When the inlet pressure is 5 MPa, the IPEPC has a highest net power output (114.5 kW). Hence, reducing the inlet pressure can decrease the unnecessary pump work consumption. The above results show that the DHE outlet pressure of working fluid can be increased by using thermosiphon effect under the effect of gravitational field.

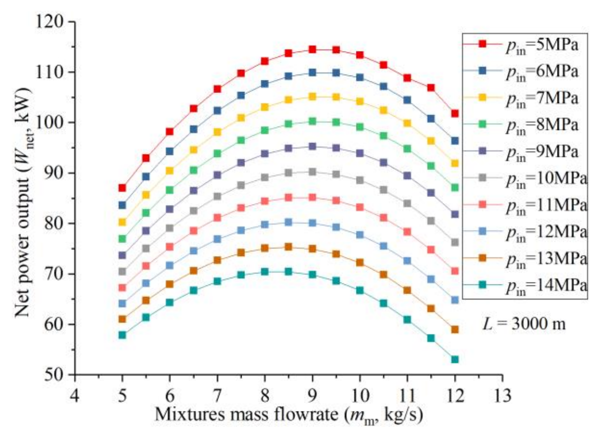

Fig. 3. Effect of the working fluid flowrates on IPEPC net power generation with respect to different inlet pressure (CO_2-R32=0.5-0.5)

Fig.4 shows the net power output comparisons among organic Rankine cycle (ORC), single-flash (SF), trans-critical CO_2 (t-CO_2) and IPEPC, with respect to different DHE length (L). When the L is 2000 m, the net power output of the IPEPC is 17.5%, 98.4% and 120% higher than that of the t-CO_2, SF and ORC respectively; whereas it is only 7.4%, 9.1% and 21.7% if the L is 3000 m. When the L is 4000 m, the SF system has the highest net power output while the t-CO_2 system has the worst power generation performance.

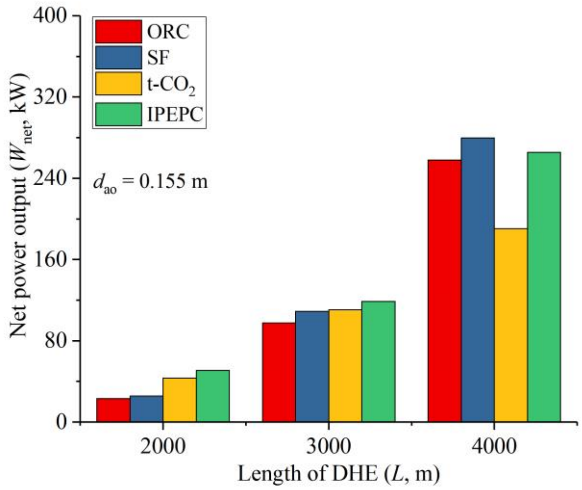

Fig. 4. Net power output comparisons among ORC, SF, t-CO_2 and IPEPC with respect to different DHE length

4. CONCLUSIONS

In this study, an increasing-pressure endothermic power cycle (IPEPC), with an increasing-pressure endothermic process in the DHE and CO_2-based mixture as working fluid, has been developed for the geothermal wells with depths ranging from 2 km to 4 km. In addition, thermodynamic performance (in terms of the net power output) has been compared between the IPEPC, ORC, t-CO_2 and SF systems. Results obtained in this study are of engineering guiding significance for hot dry rock power generation.

(1) Integrated research on hot dry rock power generation and heat extraction with utilization of an IPEPC has been completed. The increasing-pressure endothermic process and the non-isothermal condensation process can be achieved by using CO_2-based mixture working fluid in DHE and condenser respectively;

(2) Using CO_2-R32 as working fluid has the best power generation performance than other CO2-based mixtures;

(3) A lower DHE inlet pressure can improve the IPEPC net power output;

(4) In terms of net power output, IPEPC shows greater advantages compared with other systems when the geothermal well depths lower than 4000 m.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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