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Performance analysis on a hot dry rock geothermal resource power generation system based on Kalina cycle

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Abstract

Based on the conventional Kalina cycle, a hot dry rock geothermal resource power generation system is recommended in this paper. To predict the system performance, the corresponding thermal calculation model is established. A high pressure condenser and a low pressure condenser are used to condense the working fluid (Ammonia-water mixture) and the basic fluid in the recommended system, respectively, and a regenerator is adopted to recover part of exhaust heat of the turbine, at the same time to provide energy for the separation of ammonia-water mixture. The parameter performance analyses are carried out on the system. Results show that both the thermal efficiency and dynamic power recovery increase with elevation of heat source temperature, the dynamic recovery efficiency varies in the range of 8.5-18 percent, in the heat source temperature range of 150-220°C, and the geothermal recovery efficiency varies in the range of 86 to 88 percent. A relative low basic solution concentration and a high working fluid concentration is helpful to improve the system efficiency under the satisfied separation condition. The minor variation of the system efficiency with variation of circulating ratio indicates that the vary of circulating ratio due to the environmental elements will not cause great effect on system performance.

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Keywords: Hot dry rock; Power generation; Kalina cycle; Thermal performance

1. Introduction

Hot dry rock, as a kind of huge geothermal resources, buried deep underground 2-6 km, has attracted much attention in recent years. It widely distributed in the depths of the earth with temperature in the range of 150 °C to 650 °C. The thermal energy reserves of hot dry rock in the earth are huge. Studies have

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shown that it contains nearly 10 billion quarts of thermal energy even in shallow hot dry rock area, it is 300 times more heat of the fossil fuels (coal, gas and oil) on the earth [1-5]. Hot dry rock can be used for heating or power generation. The concept of hot dry rock power generation is firstly put forward by Los Alamos laboratory at university of California in the 1970s [6]. The basic idea is to establish an artificial heat reservoir through the water pressure blasting or other methods in the dense underground hot dry rock area. Then, the cold water on the ground is injected into the heat reservoir to obtain heat energy, the obtained hot water or vapor is then extracted out of the ground to generate power. In 1970, the first hot dry rock mining test was successfully realized in the United States. In recent years, through the efforts of all countries and international cooperation, Japan, Germany, the United States and other developed countries successfully tested hot dry rock power generation systems, the relevant technologies are tested and mastered [7-10]. In addition, the power generation capacity of the pilot system continues to increase, from 3 MW to 11 MW. Certainly, there are still a lot of work to do to achieve commercial operation and development of this technology. How to use the hot dry rock resources effectively, optimize the hot dry rock power generation system, and improve the efficiency of the system are still the problems need to be solved.

Kalina cycle was proposed by Alexander Kalina [11] in 1984 to replace the traditional thermodynamic cycle (such as Rankine cycle) as the bottom cycle in combined power cycle system of low temperature heat source. It has been proved that Kalina cycle can achieve a higher power output from a specified geothermal heat source when compared with organic Rankine cycle [12-16]. The ammonia-water mixture is used as the working fluid in Kalina cycle, which results in a better heat transfer matching relations in medium or low temperature source applications due to the non isothermal phase change process of the medium and the medium concentration changes in circulation. Due to the relative lower critical temperature of ammonia-water mixture compared with pure water, it has been proved that the Kalina cycle has more advantages in medium or low temperature heat source applications, such as geothermal power [17], solar power generation [18,19], recovery of industrial waste heat[20], as a bottom cycle of generating unit [21-23], as well as used as circulating system of electric-cold cogeneration unit [24].

The water or vapor temperature out of the production well of hot dry rock system is in the range of 150 °C to 250 °C. It is belonging to low temperature heat source, and is particularly suited for Kalina cycle power generation. The literature survey shows that although great efforts have been done for hot dry rock power generation and Kalina cycle power generation, respectively, the hot dry rock power generation system based on Kalina cycle is not existed. In this paper, a hot dry rock power generation system model based on conventional Kalina cycle is recommended. Through thermodynamics analysis, the system performances are analyzed theoretically. The effect of major operation parameters on system thermal performances are discussed comprehensively.

2. System modeling

2.1. System description

The proposed hot dry rock systems are mainly including a power generation cycle and a heat extraction cycle. This study lays particular emphasis on qualitative analysis on Kalina power generation cycle, which utilizes ammonia-water mixture as the working fluid. The schematic diagram of the system is shown in Fig.1. The high pressure cold water (B2) by high pressure booster pump is firstly injected into the underground artificial heat reservoir. Then, the cold water is heated by high temperature rock into hot water or steam. The pressured hot water (B3) is extracted out of the ground through production wells. The filtered hot water (B4) through filter is used to heat the ammonia-water mixture in the evaporator. The

cooled water (B5) after evaporator is again injected in the injection wells by a high-pressure pump. The heat extraction cycle from hot dry rock is finished.

The working fluid in Kalina cycle (9) is heated and evaporated in evaporator. The superheated ammonia-water mixture vapor (10) is then expanded in the turbine to generate electricity by using a generator. The exhaust steam from the turbine (11) after releasing the heat in regenerator, enters into the mixer 1, and mixes with rich water solution (14) coming from the separator, then the basic solution of steam with relative low concentration (13) is got. The basic solution of steam is then condensed in low pressure condenser to get the saturated liquid (15). After pressurizing, the saturated liquid is separated into two parts in distributor, one stock of solution (2) is heated by flowing through regenerator, and separated into rich water solution (7) and rich ammonia solution (6) in Distillation type separator. The rich ammonia solution (6) is mixed with the other stock of solution (3) coming from distributor in the mixer 2 to get the working fluid (4). Then, the working fluid (4) is condensed into saturated working fluid (8) in the high pressure condenser, and pressurized to working fluid (9) before entering the evaporator, thus the Kalina cycle is completed.

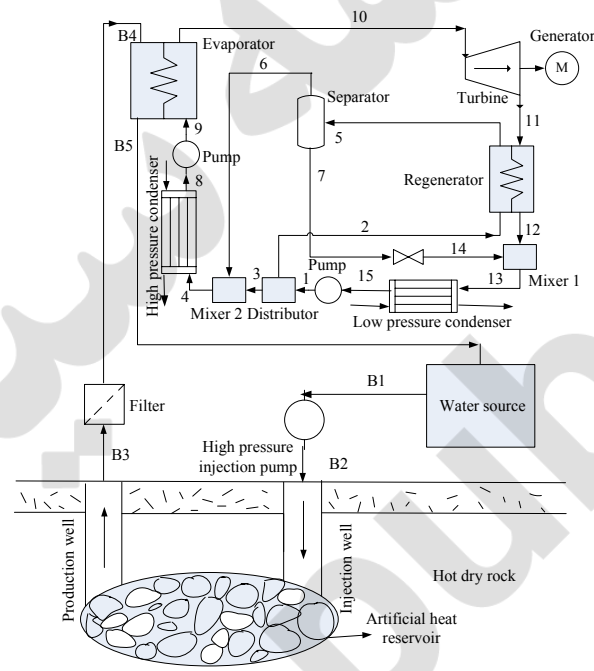


Fig.1 Sketch of a hot dry rock power generation system based on Kalina cycle

2.2. Basic parameters and general assumptions

In the above Kalina cycle power generation system, water is used to cool the ammonia-water mixture fluid in low pressure condenser and high pressure condenser, respectively. The calculation equations is summarized in Table 1. In the Table, G is the mass flow rate, $F=G_1/G_{10}$ is the ratio of the flow rate of basic fluid to the flow rate of working fluid, h is the enthalpy of the working fluid, Δt is the temperature difference. C_{ph} is the specific heat of hot water, t is temperature. Considering that the water loss exists in hot dry rock heat extraction system, the concept of geothermal recovery efficiency is recommended. It is the ratio of heat absorption rate in Kalina cycle to the maximum heat extraction rate from hot dry rock

system without water losses, and the temperature difference between the outlet of evaporator and the water injection entry of heat extraction system is also considered in this definition. $Q_0 = G_{B1} C_p (T_{B4} - T_{B1})$ is the maximum heat extraction rate from heat reservoir without water losses in heat extraction process. The concept of dynamic recovery efficiency is used to characterize the energy utilizing degree of hot dry rock resource and can more accurately reflect the power generation capacity of the system.

Table 1. Calculation equations in system analysis

Items	Equations	Numbers
Mass flow rate of cooling water	$G_{C1} = G_{10} F (h_{13} - h_{15}) / c_p / \Delta t_{C1}$	(1)
	$G_{C2} = G_{10} (h_4 - h_8) / c_p / \Delta t_{C2}$	(2)
Flow rate of hot water coming from production well	$G_h = G_{10} (h_{10} - h_9) / C_{ph} / (t_{B4} - t_{B5})$	(3)
Power output in turbine	$W_T = G_{10} (h_{10} - h_{11})$	(4)
Power consumptions of two pumps	$W_{P1} = G_1 (h_1 - h_{15}), W_{P2} = G_{10} (h_9 - h_8)$	(5)
Heat absorption rate of the system	$Q_e = G_{10} (h_{10} - h_9) = G_h C_{ph} (t_{B4} - t_{B5})$	(6)
Heat release rate of the system	$Q_c = G_1 (h_{13} - h_{15}) + G_{10} (h_4 - h_8)$	(7)
Net power output in the cycle	$W_{net} = W_T - W_{P1} - W_{P2}$	(8)
Thermal efficiency based on the first law of thermodynamics	$\eta = W_{net} / Q_e$	(9)
Geothermal recovery efficiency	$\eta_h = Q_c / Q_0 = \frac{G_h (t_{B4} - t_{B5})}{G_{B1} (t_{B4} - t_{B1})}$	(10)
Dynamic recovery efficiency	$\eta_0 = W_{net} / Q_0 = \frac{W_{net}}{Q_e} \times \frac{Q_e}{Q_0} = \eta \eta_h$	(11)

Moreover, the following assumptions is applied to the system in calculation: (1) The system is running in a stable condition; (2) The ammonia-water mixture solution is in a saturated liquid state at the export of the two condensers; (3) The inner flow resistance in the heat exchangers is ignored; (4) The pumps and throttle valves have no effect on ammonia-water solution state, only the pressure variation is considered; (5) All of heat exchangers are countercurrent flow, and the steady heat transfer is occurring. Based on these assumptions, the system performance can be analyzed. The necessary initial conditions that need to be given including the heat source temperature t_h , the concentration of working fluid x_w , the cooling water temperature, t_{c1} , and the mass flow rate through the turbine G_{10} . The literature survey is shown that the outlet water temperature of hot dry rock heat extraction system is related with the rock temperature, thermal conductivity of the rock, as well as the volume of the reservoir. In this study, the outlet water temperature is set in the range of 150-250°C. The water wastage rate is set as a constant value of 10 percent. Considering that the water out of the evaporator is cycled in the heat extraction system, 5°C temperature difference is assigned between outlet of the evaporator and the inlet of the injection well.

2.3. Calculation model

In system analysis, the heat source temperature t_{B4} , the inlet temperature of cooling water t_{c1} , and the concentration of ammonia-water mixture is firstly assumed. Then based on the given initial terminal temperature difference from Table 2, the working fluid temperature at outlet of evaporator can be

calculated as $t_{10}=t_{B4}-\Delta t_{p,B4-10}$. The dew point temperature of working fluid is calculated as $t''_{10}=t''_{10}-\Delta t_{sh}$. Then the evaporative pressure P_g at point 10 is got (i.e. p_g is determined by t''_{10} and x_w). Sequentially, the state parameters at point 8, 15 and 1 can be determined. Based on above determined parameter and the initial assumptions, it can be known that $P_{11}=P_1$, $s_{11}=s_{10}$, $x_{11}=x_w$, so the theoretical enthalpy and the actual enthalpy at point 11 is determined. Then the circulation ratio is assumed. The working fluid concentration and basic solution concentration, the rich water concentration x_7 at the outlet of separator is determined. $P_7=P_m$, and the solution at point 7 is saturated liquid, so $T_7=T_5$ is determined. Afterward, by checking whether or not the temperature difference between point 5 and 11 matches the specified temperature terminal difference of regenerator, and checking whether or not the temperature at point 5 matches the separation condition. If above condition is not satisfied, to correct the circulation ratio, and back to calculation until reaching the condition. After that, the state parameters at other points including point 6, 1, 2, 3, 9, 4, 12, 13, and 14 can all be determined based on the acquired parameters on adjacent points, respectively. The software MATLAB2010a combined with REFPROP8.0 is adopted to complete above calculations. REFPROP8.0 is a thermophysical properties calculation software of mixtures exploited by American national standards institute of technology (NIST).

Table 2. Selected initial conditions in simulation

Heat exchangers	Symbol	Recommended ^[25]	Selected
Terminal temperature difference at Cold side of evaporator	$\Delta t_{p,B5-9}$	5°C-15°C	10°C
Terminal temperature difference at hot side of evaporator	$\Delta t_{p,B4-10}$	5°C-15°C	5°C
Terminal temperature difference at cold side of condenser	$\Delta t_{p,15-ci}(\Delta t_{p,8-ci})$	4°C-8°C	5°C
Super heat degree of turbine	Δt_{sh}	5°C-10°C	5°C
Terminal temperature difference at hot side of regenerator	$\Delta t_{p,11-5}$		$\geq 5^\circ\text{C}$
Temperature rise of cooling water in condenser	Δt_c		8°C
Adiabatic efficiency of turbine	η_T		0.8

3. Results and Discussion

A set of initial parameters should be set to check the system performance and to obtain a set of property performance parameters as the benchmark to analyze the system's performance. The assigned parameters are heat source temperature $t_h=200^\circ\text{C}$, cooling water temperature $t_{ci}=25^\circ\text{C}$, working fluid concentration $x_w=0.45$, basic solution concentration $x_b=0.3$, circulation ratio $F=5$. Then the system performance is calculated. The results shown that Net output of the system is 406.92 kW, The thermal efficiency of the cycle is 17.06% with geothermal recovery efficiency of 87.33% and dynamic recovery efficiency of 14.89%. From these results, it is proven that the simulation programs designed for Kalina cycle hot dry rock power generation system is rational. As a result, the corresponding parameter performance analyses of the system are carried out.

Based on above reference conditions, the effect of cooling water temperature and heat source temperature on system performance is investigated firstly as shown in Fig.2 and Fig.3. Figure 2 gives the variation of net power output and thermal efficiency of the cycle with variation of heat source temperature and the cooling water temperature. It is known that the initial pressure (evaporative pressure) increases

with the rise of heat source temperature, and the condensing pressure decreases with decrease of cooling water temperature. Both of these will increase the pressure difference in the turbine appropriately, which will make the turbine more productive. It has been proved by this calculation as shown in Fig.2. Both the net power output of the system and thermal efficiency are increasing with elevation of heat source temperature, but the increasing rate is lowered slightly due to the fact that the power consumption of the working fluid pumps is increasing.

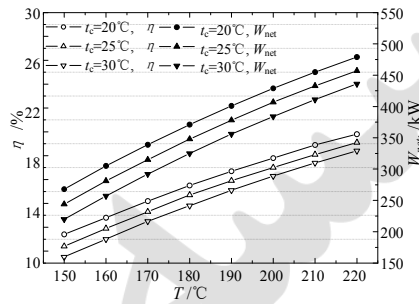


Fig.2 The temperature dependent net power output and thermal efficiency of the cycle

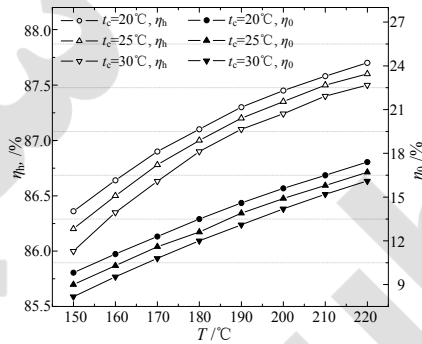


Fig.3 The temperature dependent geothermal recovery efficiency and dynamic recovery efficiency

Figure 3 shows the variation of geothermal recovery efficiency and dynamic recovery efficiency of the system with variation of heat source temperature and the cooling water temperature. They have the similar variation trend with the variation of net power output and thermal efficiency as anticipated. The value of geothermal recovery efficiency depends on both initial and discharging temperature of heat source. Although the discharging temperature will rise with elevation of initial temperature of heat source, it's effect on system efficiency is minor. It should be noticed that although a lower cooling water temperature can improve the system performance and efficiency. While, a too low cooling water temperature may result to a wet steam state at the last stage of turbine, which may cause corrosion of last stage blade of turbine. It should be avoided in system designing.

Figure 4 gives the basic solution concentration dependent thermal efficiency and dynamic recovery efficiency of the system. It is shown that the thermal efficiency and dynamic recovery efficiency are both decreasing with elevation of basic solution concentration. At the fixed initial parameters of the working fluid entering the turbine, the basic solution concentration's elevation will result in an increase of condensing pressure and temperature in low pressure condenser, which will lead to the power output of turbine reducing. It seems that a relative low concentration is more benefit to improve the efficiency of the system. While, it should be noticed that the turbine exhaust temperature decrease with lower of basic

solution concentration will result in a decrease of separation temperature in separator, which is disadvantage to ammonia-water mixture separation. Enough heat must be guaranteed to satisfy the separation process. Considering these two aspects, a compromise lowest value of basic solution concentration is required to guarantee both the solution separation requirement and the relative high system efficiency.

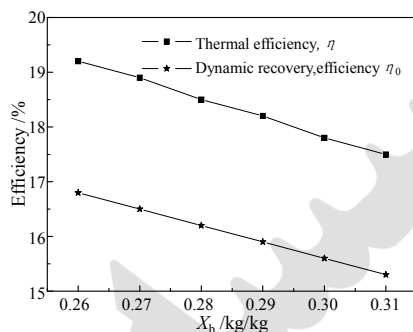


Fig.4 The basic solution concentration dependent thermal efficiency and dynamic recovery efficiency of the system

Figure 5 gives the circulating ratio dependent thermal efficiency and dynamic recovery efficiency of the system. It is shown that both the thermal efficiency and dynamic efficiency reduce slightly with the increase of circulating ratio. This reduction is due to the fact that the power consumption of low pressure pump is increased as the flow rate of the basic solution through the low pressure condenser is increasing with increase of circulating ratio. The power output of turbine will be not changed with vary of circulating ratio as shown in Fig.5. The minor variation of the system efficiency with variation of circulating ratio indicates that the vary of circulating ratio due to the environmental elements will not cause great effect on system performance. Therefore, the stability of the Kalina cycle can be guaranteed.

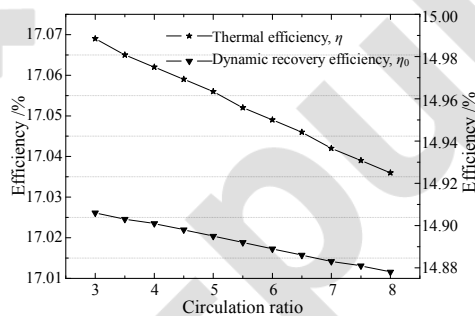


Fig.5 The circulating ratio dependent thermal efficiency and dynamic recovery efficiency of the system

4. Conclusions

Hot dry rock, as an environmental friendly and almost inexhaustible new energy buried under the ground, is a kind of underexplored low temperature resource. It is of great significance to actively promote the development and utilization process of hot dry rock resource. Based on the Kalina cycle, a hot dry rock power generation system is recommended in this paper. The corresponding thermal calculation model is built to investigate the system performance. The rationality is confirmed by an assigned operating condition. The results show that a relative low working fluid concentration is

necessary to realize the circulation of the system due to the fact that the heat source temperature of 150-200°C has exceeded the critical heat source temperature. Both the thermal efficiency and dynamic power recovery efficiency increase with elevation of heat source temperature. The dynamic recovery efficiency varies in the range of 8.5-18 percent in the heat source temperature range of 150-220°C with geothermal recovery efficiency varies in the range of 86 to 88 percent. A relative low basic solution concentration and a high working fluid concentration are helpful to improve the system efficiency under the satisfied separation condition. The minor variation of the system efficiency with variation of circulating ratio indicates that vary of circulating ratio due to the external environmental conditions will not cause great effect on system performance.

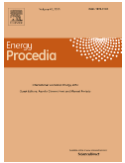
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Biography

Gaosheng Wei, Born in China in 1975. PHD (2006) from University of Science and Technology Beijing major in Thermal Engineering. Associate professor (2009-present) at North China Electric Power University. The research is focused on thermophysical properties of materials, renewable energy systems. Over 50 papers have been published in journals.