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Analysis of a Mid-temperature Solar Power System Using Chemical-looping Combustion

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Abstract—In this paper, a solar hybrid power generation system with chemical looping combustion (CLC) is analyzed. Using concentrated solar thermal energy at about 500℃ as a heat source to drive the endothermic reduction of metal oxide with CH4 in the fuel reactor, and then the metal oxide is transported into the air reactor to be oxidized for regeneration. After that, the flue gas from the air reactor is further drive the gas turbine for power generation. In this paper, the behavior of thermodynamic performance is analyzed. Two important indicators of fuel energy saving ratio (FESR) and exergy efficiency are used to evaluate. The FESR and the exergy efficiency would be expected to reach 34.14% and 49.50%, respectively. At last, the feasibility of the key process was verified by experiments in honeycomb reactor. The oxygen transfer rate and oxygen loss capacity of the reaction process showed exciting performance. Also, the redox stability of oxygen carrier had little changes after repeated cycles.

Keywords—solar thermochemical power system, chemical-looping combustion, honeycomb reactor

I. INTRODUCTION

Concentrating solar power (CSP) technology has been got rapid development after the energy crisis erupted in the 1970s; however, the intermittence of solar energy has impeded its development and application in the current. Increasing attention has been paid on thermal energy storage (TES) technologies and solar-hybrid system for their potential to solve the unstable problem caused by solar and to effective use of solar thermal energy [1-3].

The current main thermal energy storage technologies include three types, sensible heat storage, latent heat storage and thermochemical storage [4-7]. Though the sensible heat TES technology is the only commercially viable method for storing thermal energy in large scale CSP plants, the low volume specific heat capacity will lead to its large equipment for solar thermal energy storing and limit its further development [4,5]. Latent heat TES involves a phase change, due to the large phase change latent heat of phase change materials (PCM), the volume specific heat capacity of latent heat storage is larger than sensible heat storage. But the low heat conductivity of PCM of latent heat storage will cause more heat loss, and this is the main obstacle in the development of latent heat TES technology, now many researchers are trying to use various methods to solve this problem [6]. While thermochemical TES involves an endothermic chemical reaction, its volume specific heat capacity is larger than sensible TES and latent TES, so, the thermochemical TES is the most promising heat storage technology. But the current chemical reactions used for energy storage generally work at high temperatures (⩾ 800℃), and the thermochemical TES materials mostly are gases, need to be stored at very high pressure, this is a huge challenge for storage containers [7].

Solar-hybrid system is another important technology in CSP plants, for example, as combined cooling, heating, and power (CCHP) systems. So far, many different kinds of solar thermal CCHP systems have been investigated by researchers from all over the world. Although solar thermal CCHP technology is considered a promising power technology, the predicament is that direct combustion of fossil fuel still causes the problem of CO2 capture with high energy penalty [8-10].

In 1994, Ishida and Jin proposed a novel gas turbine cycle with chemical-looping combustion (CLC), in which no extra energy is needed for CO_2 separation. The chemical-looping combustion system has revolutionized the traditional utilization of hydrocarbons through direct combustion [11]. The hybridization of a CLC power cycle with solar thermal energy was first proposed and modified by Hong and Jin in 2005 and 2006, respectively [12,13]. These investigations identified an important advantage of hybrid solar-CLC systems, in that solar energy can be converted to chemical energy at low temperatures and released at higher temperature. Then, in 2013, Jafarian el al. proposed a hybrid solar and chemical looping combustion system for solar thermal energy storage, which is a new kind of thermochemical TES used for high temperature (more than

800℃), it has a large volume specific heat capacity and not need tough conditions for the store of storage materials [14].

The objectives of this paper is to propose a solar thermochemical hybrid power system with solid thermochemical energy storage and CO_2 capture using chemical-looping combustion, to evaluate the thermodynamic performance, and to prove the feasibility of the key process by experiment.

Nomenclature

CLC	Chemical-looping combustion
CCHP	Combined cooling heating and power
I	Radiation
S	Area (m^2)
FESR	Fuel energy saving ratio
η	Efficiency
Q	Quantity of heat
W	Work
ω	Solar energy generating systems
COP	Coefficient of performance
F	Fossil fuel consumption

II. System Description

A. System

Fig. 1 illustrates the schematic diagram of the proposed solar-hybrid CCHP system. The new system consists of three main subsystems: the solar-hybrid power subsystem, the solar-CLC storage subsystem, and the waste heat utilization subsystem.

Solar-hybrid power subsystem. As shown in Fig. 1, CH_4 is introduced into the reduction reactor, where an endothermic reaction ($CH_4 + 4NiO \rightarrow CO_2 + 2H_2O + 4Ni$) driven by solar thermal energy (500℃) takes place, the metal oxide NiO is reduced into metal Ni through the reduction reaction. The metal Ni is introduced into the oxidation reactor, oxidized by compressed air ($4Ni + 2O_2 \rightarrow 4NiO$), and the solar energy and chemical energy of CH_4 have been converted into the chemical energy of metal Ni through the reduction reaction are released in the form of heat through oxidation reaction. Then, the gas turbine is driven by the high temperature flue gas, and the output power is the production.

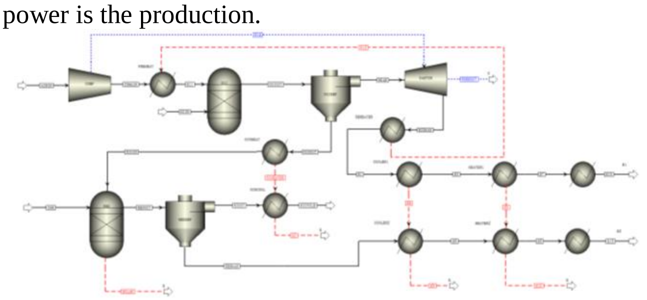

Fig. 1 Schematic diagram of the proposed solar-hybrid CCHP system

Solar-CLC storage subsystem. When the solar energy is sufficient, solar thermal energy at approximately 500℃ is used to supply the reaction heat of the reduction, meanwhile, the solar energy is converted into the chemical energy and stored in the solid Ni. If the solar energy is not enough to drive the solar-CLC storage subsystem, the solid fuel Ni stored in the storage would be provided to the solar-CLC storage subsystem to maintain the output power in the fixed value.

Solar-CLC storage subsystem. The temperature of exhaust gas from gas turbine is still very high, there will be a large amount of energy wasted if the gas is directly discharged into the environment. So, in this study, reheater and cooling/heating unit are used to recycle the thermal energy of flue gas from gas turbine.

Due to the inherent characteristics of chemical-looping combustion, the proposed solar thermochemical hybrid system in this paper can realize CO_2 capture without extra energy. In addition, for the use of solid thermochemical energy storage, the proposed system not only can realize integration of energy storage material and power fuel, but also with higher energy storage density than the traditional thermal energy storage technologies at the same temperature.

B. Reactor characteristics

The cyclic reaction of chemical-looping in the system proposed is studied experimentally. The experiments are carried out on a honeycomb reactor. Fig. 2 presents the configuration of the honeycomb CLC reactor. The honeycomb chamber is adapted, and its shape is a cylindrical monolithic block. On the surface of the honeycomb chamber, there is a series of axial micro-channels. The supporting material of the honeycomb chamber is consist of oxygen carriers, which realizes the integration of oxygen carrier and reactor. When the reactant gas is fed into the reactor, it traverses the honeycomb chamber through the axial micro-channels. In this way, there is a potential in increasing contact area and disturbance between the oxygen carriers and the reactant gas, enhancing the reaction kinetics of the CLC reactions.

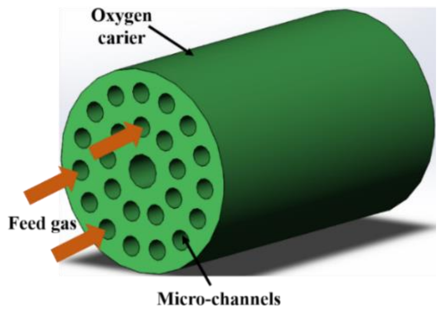

Fig. 2 Conceptual of the honeycomb CLC reactor

III. Thermal Performance Analysis of the System

A. Simulation conditions

In this study, Aspen Plus was used to model the system and analyze the thermal performance. The thermodynamic performance calculation model of the system is shown in Fig. 1. In the simulation process, Gibbs free energy model is used for chemical-looping cycle reaction. The GTU-2.5P gas turbine manufactured by Aviadvigatel is selected as the turbine, and the LS-2 trough collector designed by LUZ company is adopted for the medium-temperature solar collector. Besides that, the heat loss of the main heat transfer unit and the pressure loss in the system pipelines are ignored, and the ambient temperature is set at 25 oC. The other relevant simulation parameters are shown in Table. 1.

Table. 1 Main assumptions for the proposed system

Parameter	Value
Solar radiation intensity	800 W/m2
Concentrated ratio	82
Heat collection efficiency	0.65
Reduction temperature	500℃
Oxidation temperature	950℃
Circulating pressure ratio	6
Refrigeration temperature	7℃
Heater outlet temperature	70℃
Heat transfer temperature difference	20℃

B. *The indictor for evaluation*

In order to evaluate the thermodynamic performance of the solar energy solid fuel storage method comprehensively and objectively, the fossil energy saving ratio is used to evaluate the overall performance of the system. The calculation equation of the fossil energy saving ratio is shown in Eq. (1) [15] :

$$FESR = \frac{F_{sep} - F_{CCHP}}{F_{sep}} = \frac{\left(\frac{W_{net}}{\eta_{w,sep}} + \frac{Q_c}{COP} + \frac{Q_h}{\eta_{h,sep}}\right) \Big/ Q_{HHV} - F_{CCHP}}{\left(\frac{W_{net}}{\eta_{w,sep}} + \frac{Q_c}{COP} + \frac{Q_h}{\eta_{h,sep}}\right) \Big/ Q_{HHV}} \quad (1)$$

where F_{sep} is the fossil fuel consumption in an individual system, F_{CCHP} is the fossil fuel consumption in the new solar solid-fuel power generation system proposed by this study. $Wnet$, Q_c and Q_h are the net generating capacity, the cooling capacity and the heating capacity of the new system respectively. $\eta_{w,sep}$, COP and $\eta_{h,sep}$ are power generation efficiency, cooling coefficient and heating efficiency of fossil fuel direct combustion heating system respectively. Besides that, the performance parameters of the individual systems are selected as follows: power generation is 50%, refrigeration coefficient is 4.0 and boiler heating efficiency is 90%.

C. *The simulation results*

The thermal performance calculation results of the solar solid fuel source energy storage power generation system are shown in Table. 2. When the solar radiation intensity is 800 W/m2, turbine inlet temperature is 950 oC, and the pressure circulating ratio is 6, the net power generation of solar power is 3.21 kW, the solar refrigeration power is 1.97 kW and the net solar heating power is 1.53 kW, respectively. Under that condition, the net solar power generation efficiency, the net solar cooling efficiency and the net solar heating power efficiency are 32.14%, 19.73% and 15.27% respectively. The corresponding system fossil energy saving rate is 34.14%. Also, the exergy balance calculation results of the system is shown in Table. 3. It could be seen from the Table. 3 that the exergy efficiency of the system is up to 49.50%.

Table. 2 Thermal performance of solar solid fuel source energy storage power generation system

Parameter	Energy (kW)	Ratio (%)
CH_4 input energy	40.38	80.15
Solar input energy	10.00	19.85
Output power	20.64	40.97
Cooling	14.62	29.02
Heating	14.74	29.25
Solar net power generation	3.21 kW	
Solar net cooling	1.97 kW	
Solar net heating	1.53 kW	
Solar net power efficiency	32.14%	
Solar net cooling efficiency	19.73%	
Solar net heating efficiency	15.27%	
Solar power share	19.85%	
Fuel energy saving ratio	34.14%	

Table. 3 Solar solid fuel source energy storage power generation system exergy balance

Item		Exergy(kW)	Ratio(%)
Exergy input	CH4	41.94	88.27
	Solar	5.57	11.73
	Total	47.51	100.00
Exergy loss	Reduction reaction	3.54	7.45
	Oxidation reaction	9.82	20.67
	Compressor	1.23	2.58
	Turbine	1.71	3.61
	Heat transfer	2.76	5.82
	Refrigeration unit	3.09	6.51
	Heating unit	0.89	1.87
	Tail gas	0.11	0.24
	Total	23.16	48.75
Exergy output	Output power	20.64	43.45
	Cooling	0.94	1.98
	Heating	1.93	4.07
	Total	23.52	49.50
Total exergy		46.68	98.25
Exergy efficiency		49.50%	

IV. SYSTEM DESCRIPTION

A. *Reaction performance*

Fig. 3 shows that the time-varying characteristics of the oxygen transfer rate of $NiO/NiAl_2O_4$ in a honeycomb reactor and a fixed-bed reactor. As shown in the figure, the rate of the oxygen loss in the honeycomb reactor is 3-4 times that in the fixed-bed reactor during the whole reduction reaction. This is mainly because the honeycomb reactor could provide better gas solid reaction kinetics for the chemical-looping combustion. It could be also seen that, the oxygen loss rate in the honeycomb reactor remains approximately unchanged at 12 mg/s in the state from 0 to 2000 s, and the oxygen loss rate decreased rapidly to 3 mg/s between 2000-2800 s. The main reason could be explained by the excellent reaction kinetics of the honeycomb reactor before 2000 s, which enables the rapid transfer of the oxygen contained in the oxygen carriers to CH_4. The oxygen storage is insufficient during the period of 2000-2800 s, resulting in a sharp decrease in oxygen loss rate.

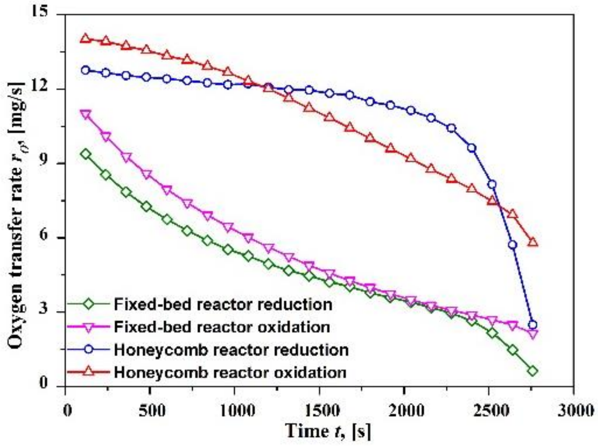

Fig. 3 Characteristics of oxygen transfer rate of NiO/NiAl2O4 with time

In the state from 0-2500 s of the oxidation reaction, the oxygen uptake rate of the reactor carrier decreased slowly from 14 mg/s to 7.8 mg/s, and after 2500 s, the oxygen uptake rate started to decrease rapidly. Because the honeycomb reactor could provide good contact between the oxygen carriers and the air, which guarantees that the oxygen carriers could absorb oxygen from the air quickly and store it. The oxygen absorption rate of honeycomb reactor is significantly higher than that of fixed-bed reactor, especially during 0-2500 s. After that, the oxygen stored in the carrier is close to the saturation state, which makes the absorption difficult. So, the oxygen absorption rate starts to decline rapidly after 2500 s.

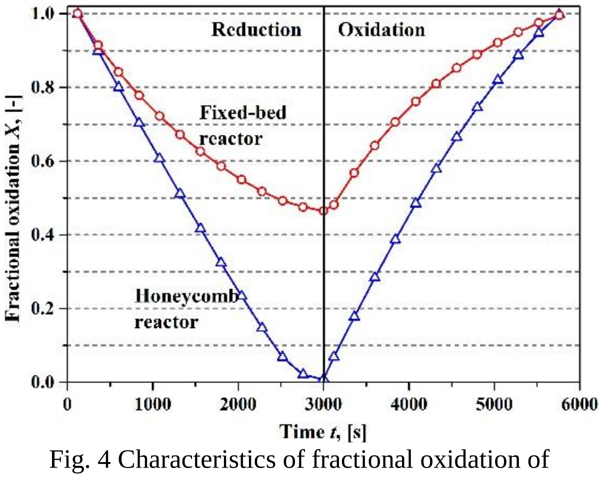

Fig. 4 Characteristics of fractional oxidation of NiO/NiAl2O4 with time

The variation characteristics of oxygen carrier oxidation degree with reaction time are shown in Fig. 4. In the honeycomb reactor, during the period of 0-2000 s in the reduction reaction, the fractional oxidation decreased from 1.0 to 0.2 in an approximately linear trend, and in the state of 2000-2800 s, the slope of the oxidation degree curve gradually slows down, and the fractional oxidation gradually decreases to 0. In the fixed-bed reactor, the fractional oxidation shows a similar downward trend, but only declines to about 0.47. The change of oxidation degree has the same trend with the change of oxygen transfer rate.

In the oxidation reaction shown in the Fig. 4, the oxidation degree of oxygen carrier in honeycomb reactor increases rapidly from 0 to 0.9 in 2500 s. After that, the rate of increase starts to slow down, and the fractional oxidation gradually increase to 1.0. The similar change trend is occurred in fixed-bed reactor. The fractional oxidation rapid rise from 0.47 to 0.9 and slowly climb from 0.9 to 1.0. the oxygen transfer rate is the main factor affecting the rate of the fractional oxidation.

B. Cyclic regeneration performance

In order investigate the cyclic regeneration performance of oxygen carrier, 150 hours of continuous experimental operation was carried out. The characteristic of cyclic oxidation degree of oxygen carrier with time is shown in Fig. 5. As shown in the figure, during the continuous operation of 150 hours, NiO/NiAl2O4 experienced a total of 30 redox cycles. At the end of the initial reduction, the oxidation degree of the oxygen carrier decreased to 0, indicating that NiO/ NiAl2O4 can be completely reduced to Ni/ NiAl2O4. At the end of the initial reoxidation, the degree of oxidation of the carrier was 1.0, indicating that Ni/NiAl2O4 could be completely reoxidized into NiO/NiAl2O4. In the 30th cycle, the oxidation degree of the oxygen carrier at the end of reduction and reoxidation is about 0.02 and 0.98, indicating that the conversion rate of NiO/NiAl2O4 oxygen carrier in the 30th cycle was about 98%.

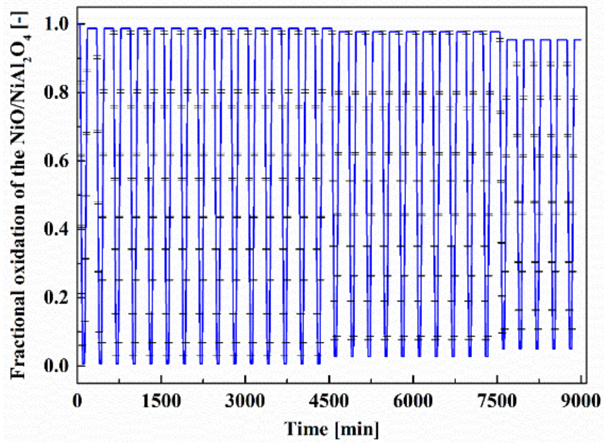

Fig. 5 Redox stability of NiO/NiAl2O4 for 150 h continuous operation

V. 5. Conclusion

A solar-hybrid power generation system with chemical-looping combustion was analyzed. The exergy efficiency of the solar-hybrid system can reach 49.50% at design point. The annual fuel energy saving ratio of the solar-hybrid system can be reach 34.14%, the solar power share are 19.85%. The CH_4-fueled CLC integrated with the solar thermochemical process, which are the core technology of the proposed system, were also investigated with the aid of experiments in honeycomb reactor. The results showed that both the reduction and oxidation reactions are showed exciting reaction performance. The oxygen transfer rate and oxygen loss capacity of the reaction process were greatly improved, compared with the fixed-bed reactor. Also, the redox stability of oxygen carrier had little changes after repeated cycles.

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