Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-45600

A SOLAR-HYBRID POWER PLANT INTEGRATED WITH ETHANOL CHEMICAL-LOOPING COMBUSTION

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ABSTRACT

In this paper, a new solar hybrid gas turbine cycle integrating ethanol-fueled chemical-looping combustion (CLC) has been proposed, and the system was investigated with the aid of the Energy-Utilization Diagram (EUD). Chemical-looping combustion consists of two successive reactions: first, ethanol fuel is oxidized by metal oxide (NiO) as an oxygen carrier (reduction of metal oxide); secondly, the reduced metal (Ni) is successively oxidized by combustion air (the oxidation of metal). The reduction of NiO with ethanol requires a relative low-grade thermal energy at 150-200^{o}C. Then concentrated solar thermal energy at approximately 200-300^{o}C can be utilized to provide the process heat for this reaction. The integration of solar thermal energy and CLC could make the exergy efficiency and the net solar-to-electric efficiency of the system more than 54% and 28% at a turbine inlet temperature (TIT) of 1288^{o}C, respectively. At the same time, the variation in the overall thermal efficiency (η) of the system with varying key parameters was analyzed, such as Turbine Inlet Temperature, pressure ratio (π) and the

temperature of reduction reactor. Additionally，preliminary experiments on ethanol-fueled chemical-looping combustion are carried out to verify the feasibility of the key process. The promising results obtained here indicate that this novel gas turbine cycle with ethanol-fueled chemical-looping combustion could provide a promising approach of both efficient use of alternative fuel and low-temperature solar thermal and offer a technical probability of combining the chemical-looping combustion with inherent CO_2 capture for the alternative fuel.

INTRODUCTION

Solar energy is considered to be a promising method to solve the problems caused by utilization of fossil fuel for its vast reserves and cleanness. At present, solar energy conversion technologies face cost and scalability hurdles in the technologies required for a complete energy system. To provide a truly widespread primary energy source, solar energy must be captured, converted, and stored in a cost-effective fashion [1]. Solar thermochemical processes incorporating fossil fuels are receiving heightened attention as a potential and highly flexible contemporary and future energy system, because it is ecologically attractive and it broadly converts solar energy into chemical energy carriers.

Solar thermochemical programs in Switzerland and Germany took off in the early 1990s [2-6]. At present, most of the solar thermochemical processes focus on high temperature, ranging from 1000°C to 1500°C [2-8], which is suitable to split water and CO_2 by using catalysts to produce H_2, CO and O_2 in separate steps to solve separation problems. A group led by Aldo Steinfeld cycles a catalyst between metallic zinc and zinc-oxide; researchers at the German Aerospace Center in Cologne and Almeria, Spain, use their own blend of iron oxide-based catalysts; groups at the California Institute of Technology and the University of Minnesota have conducted experiments with a promising catalyst based on the metal ceria. For now, however, none of these catalysts is satisfying enough. Then, improving catalyst efficiency and getting the price down are the hurdles high-temperature solar thermochemistry researchers have to leap.

On the other hand, with the development of alternative fuels such as methanol or ethanol, there is a great potential application in the power generation sectors. Especially for China, where biomass provides a kind of abundant energy resource, ethanol is expected to be economically produced from biomass due to increasing efficiency of turning biomass to ethanol. However, when alternative fuel is being converted into thermal energy to generate electricity by traditional combustion in the conventional power plant, there is a serious issue that there are yet both the largest exergy destruction of chemical energy and high energy penalty for CO_2 removal due to containing carbon. Hence, one of the biggest potential for the development of the next-generation power plant using alternative fuel would be directed toward the new approach of fuel conversion.

Chemical-looping combustion is proposed by Ishida and Jin in 1994 and it is considered to be one of the most attractive energy efficient methods for CO_2 capture from fuel conversion in the combustion process [9-13], as shown in Fig.1. CLC using alternative fuel driven by low-temperature solar energy can be an attractive candidate [14-16], simultaneously to achieve the reasonable utilization of carbon fuel and avoid the problems encountered in high-temperature solar thermochemical process. Ethanol as reducing agents allow the reduction of nickel-oxide (NiO) at more moderate and technically feasible temperature, about 200-300°C. And, the low-temperature solar thermal energy is used, endothermic or carbothemic reduction results in metal products that can be used for producing electricity at high efficiency. The advantages of the new system are three-fold:

- By utilization of low-temperature solar thermal energy to drive the reduction reaction, benefits such as ease of handle, accurate tracking of solar concentrators, and low-cost investments can be achieved in the process.
- The chemical-looping combustion of alternative fuel reduces the exergy destruction of chemical energy and fulfills high efficient utilization of fuels.
- The gas product, discharged from the reaction reactor, consisting mainly of CO_2 and water vapor. Therefore, using simple condensing method can separate CO_2 from water with no extra energy penalty or special separator device.

The objective of this paper is (i) to propose a new scheme of low-temperature solar thermochemical process combined with chemical-looping combustion for generating electricity; (ii) to assess plant configuration and identify the characteristics of this proposed cycle with the aid of graphical exergy methodology; (iii)to analysis the variation in the overall efficiency of the system with varying key parameters; (iv)to carry out preliminary experiment to verify the possibility of solar-driven alternative fueled CLC.

NOMENCLATURE

CLC	Chemical-looping combustion
EUD	Energy-utilization diagram
HRSG	Heat recovery steam generator
OXD	Oxidation reactor
RED	Reduction reactor
TIT	Turbine inlet temperature
A_{ed}	Energy level of energy donor
A_{ea}	Energy level of energy dacceptor
A_{Ni}	Energy level of solid particle Ni
T	Temperature (^{o}C)
T_0	Ambient temperature
ΔEXL	Exergy destruction in the solar thermochemical process

GREEK LETTERS

η_{ex}	Exergy efficiency
η_{th}	Thermal efficiency

SUBSCRIPTS

comp	Compressor
ex	Exergy
ed	Energy donor
ea	Energy acceptor
f	Fuel
comb	Combustion
GT	Gas turbine
ST	Steam turbine

1 DESCRIPTION OF SOLAR-DRIVEN ETHANOL-FUELED CHEMICAL- LOOPING COMBUSTION

A new system employing ethanol-fueled chemical-looping combustion and solar thermal energy between 200^{-}300^{o}C is proposed, as shown in Fig.2. Solarized chemical-looping combustion consists of two successive reactions: (1) solar driven NiO reduction with ethanol fuel and (2) oxidation of the resulting Ni with air. The ethanol fuel (point 6) is introduced to the solar-fuel reactor [Red, as shown in Fig.1] and reacted with the pellet or spherical-shaped NiO particles, where the thermochemical reaction $C_2H_5OH+6NiO \rightarrow 6Ni+2CO_2+3H_2O$ (ΔH^0_{Red}=203.2kJ/mol) takes place, producing carbon dioxide, water vapor, and solid fuel Ni. Since the reduction of NiO with ethanol fuel can be accomplished in the range of 150–250^{o}C (which is much lower than other hybrid solar/fossil processes that require temperatures above 800^{o}C), relatively low-grade solar thermal energy is utilized to drive this endothermic reaction. In this cycle, the receiver consists of an insulated fixed-bed tubular reactor made of copper with a ceramic solar-selective absorber surface, surrounded by a transparent glass tube, which is directly heated by concentrated solar energy through a central receiver system.

Subsequently, the solid particle Ni produced from the solar fuel reactor (stream 12) is transported to the air reactor (Oxd) where it is oxidized with pressurized air from the compressor (previously preheated by the exhaust gas from GT1, point2). The oxidation reaction is strongly exothermic at 1288^{o}C ($6Ni+3O_2 \rightarrow 6NiO$, ΔH^0_{Oxd}=-1440kJ/mol), yielding NiO and effluent gases containing N_2 and O_2. The solid NiO as a looping material is cyclically used between the fuel reactor and the air reactor. Endothermic reduction ($NiO \rightarrow Ni$) is driven by low-temperature solar thermal energy. The high gas velocity may provide the driving force for carrying away the particles from the air reactor, and the NiO particles are recovered by a cyclone and fed to the fuel reactor. From the fuel reactor, the Ni particles are returned to the air reactor by means of gravity. In addition, suitable physical strength of the looping particles of NiO in the cyclic reaction can be kept by the addition of binding materials.

The effluent gases from two separate reactors are sent to individual turbines to generate power. One stream (stream 4) containing mainly N_2 and O_2 at a temperature of 1288^{o}C is introduced into the turbine GT1, while the other stream containing CO_2 and H_2O at a temperature of 1260^{o}C, from the gas-solid heat exchanger, is fed to GT2. The thermal energies of the exhausts from the two turbines are recovered by the Heat Recovery Steam Generator (HRSG) to generate steam to drive the steam turbine. Finally, the flue gas at around 91^{o}C and 1.0 bar (stream 11), only composed of 33% CO_2 and 67% H_2O corresponding to volume composition, is cooled down and condensed, and then CO_2 is easily separated with a low energy requirement.

2 SIMULATION AND EVALUATION OF THERMO-DYNAMIC PERFORMANCE

2.1 Operation conditions and main assumptions

The proposed system was simulated with ASPEN PLUS software. The gas turbine was assumed to be based on the Mitsubishi Heavy Industries M701F4, and the cooling of turbine blades was considered. Those for the power plant are representative of combined cycle technology. To simplify the simulation, it was assumed that the system operated at a steady state. Basic characteristics and mass/energy balances of each component were calculated sequentially and iteratively until the conditions at all interconnections converge toward stable values. In the solar-hybrid reduction reactor, a temperature difference of 50℃ was considered. Table 1 summarizes the main assumptions. To evaluate the system performance, a reference system of direct combustion of ethanol combined cycle was considered.

Since this paper focuses on the potential of CLC for power generation, neither the details of reactor chemistry and kinetics, nor with the issues related to the thermo-fluid-dynamic and structural design of the reactors and their ancillary components (cyclones, feeding systems, etc.) was specifically considered. Here the CLC system is modeled based on simplifying assumptions which are insufficient to design the actual design of the CLC components, but are fully adequate to predict the heat/mass balances and thus the overall performance of the integrated CLC-CC system.

2.2 System Performance Evaluation.

Since the input resources consist of two different quantities-ethanol fuel and solar thermal energy, exergy efficiency is more effective for performance evaluation for the solar hybrid combined cycle. The net exergy efficiency of the hybrid system based on per mole of ethanol fuel is given by

$$\eta_{ex} = \frac{W}{E_f + Q_{sol,th}(1 - T_0/T_{sol})} \tag{1}$$

Where W is the work output of the proposed cycle, and E_f is the fuel exergy, $Q_{sol,th}(1\text{-}T_0/T_{sol})$ represents the exergy of solar thermal energy ($Q_{sol,th}$) absorbed by the reactor, corresponding to the work availability operating between the reactor temperature T_{sol} and the ambient temperature T_0.

Thermal efficiency of the system is denoted as:

$$\eta_{th} = \frac{W}{Q_f + Q_{sol,th}} \tag{2}$$

Where Q_f is lower heating value of ethanol fuel. In order to assess the net solar-to-electric efficiency, $\eta_{net,sol}$ is defined as:

$$\eta_{net,sol} = \eta_{opt}\eta_{absorp}\frac{W_{sol,cc} - W_{ref}}{Q_{absorp}} \tag{3}$$

Where $W_{sol,cc}$ and W_{ref} are output work of new system and reference system, η_{opt} is the optical efficiency and η_{absorp} is the solar energy absorption efficiency of a solar reactor. Here, typical value of optical efficiency (the solar field optical efficiency includes incident angle effects, solar field availability, collector tracking error and twist, the geometric accuracy of the mirrors to focus light on the receiver, mirror reflectivity, cleanliness of the mirrors, shadowing of the receiver, transmittance of the receiver glass envelope, cleanliness of the glass envelope, absorption of solar energy by the receiver and end loss) of 0.75 [17] and absorption efficiency of 0.80 [18] are taken into account for the prediction of $\eta_{\text{net,sol}}$ in the proposed system.

It was found that the exergy efficiency could be as high as 54.4% at a TIT of 1288^{o}C based on the input exergies of ethanol fuel and solar thermal energy, which was about 3.7 percentage points higher than those of the reference system with no CO_2 recovery at the same TIT. The net solar-to-electric efficiency of the new system can reach to 28.6% which is competitive with the state-of-the-art high temperature solar thermal power plant (21%) [19].

3 GRAPHICAL EXERGY ANALYSIS OF THE TWO ETHANOL-FUELED POWER-GENERATION SYSTEMS

3.1 The EUD Methodology

The graphical exergy analysis of energy-utilization diagram (EUD) is proposed by Ishida in 1982 [20]. It graphically shows the variations of energy quality and energy quantity of a process with *A-dH* coordinates. It is well known that the area below the curve, from the initial to the final state in a p-v diagram, represents the work quantity shown in Fig. 3(a), whereas the area in a T-s program is the quantities of energy such as work or heat required (or generated) as the area shown in Fig. 3(b). Also the shape of the curve represents the characteristic feature of the process, but neither diagram can give exergy consumption caused by energy transformation. The EUD is a similar diagram in which the thermodynamic property is presented as the area in Fig.3(c). Here, *dH* represents the amount of transformed energy/enthalpy of the process, is on the abscissa, and the energy level *A* is on the ordinate. The energy level *A* is a dimensionless criterion ($A=dE/dH=1-T_0\times dS/dH$, a ratio of exergy change *dE* to energy change *dH)*. Every process must have energy donor and energy acceptor. Consequently, the exergy destruction is illustrated by the shaded areas between the curves of energy donor and energy acceptor.

This methodology can be used in the optimization of solar-hybrid power generation system. Compared with the traditional exergy balance analysis, the EUD analysis method focuses on the variation of energy levels during the energy utilization process rather than only the exergy destruction obtained from the exergy value difference between the output and input of units. By making an energy-utilization diagram of the solar-hybrid power generation system, we can not only judge the feasibility of the process, but also find the process with large exergy destruction, explain it, and take measures to optimize the hybrid system by adopting EUD method. In this paper, graphical exergy analysis of each system was made by using EUD method.

3.2 Reaction Subsystem

Fig. 4 (a) and Fig. 4 (b) illustrate the EUD of reaction subsystems of ethanol-fueled direct combustion and ethanol-fueled chemical-looping combustion, respectively. As shown in Fig. 4 (a), the curve of $A_{ed,1}$, acting as energy donor, presents the energy level of the direct combustion of ethanol, and its width is identical to the heat released by the direct combustion of ethanol. The heights of $A_{ed,1}$ indicates the energy level degradation due to the transformation of chemical energy into thermal energy. The heating processes of ethanol and combustion air act as the energy acceptors, which are illustrated by the curves of $A_{ea,1}$ and $A_{ea,2}$, respectively. The shaded area between the curves of A_{ed} and A_{ea} refers to the exergy destruction caused by ethanol combustion with air. Additionally, the rectangular area of the right part of Fig. 4 (a) represents the exergy destruction caused by the mixing of input streams of air and ethanol. Consequently, the total exergy destruction of direct combustion is 441.97kJ/mol-C_2H_5OH.

For the new cycle with chemical-looping combustion, the reaction subsystem consists of two reactions: the reduction and the oxidation. As shown in Fig. 4(b), the exergy destruction of the reduction of ethanol with NiO is indicated by the shaded area on the left, while that of the oxidation of solid fuel Ni with combustion air is represented by the one on the right. In the reduction process, the energy donors of solar thermal energy ($A_{ed,1}$) supply the reaction heat for the energy acceptor of the reduction of ethanol with NiO($A_{ea,1}$). The exergy destruction of the reduction is about 87.18kJ/mol-C_2H_5OH. In the oxidation process, the curve of $A_{ed,2}$ acts as the energy donor, while $A_{ea,2}$ and $A_{ea,3}$ represents the energy acceptors. The oxidation takes place at the temperature of 1288°C. Exergy destruction of the oxidation is about 232.91kJ/mol-C_2H_5OH. Hence, the overall exergy destruction of the reaction subsystem of the new cycle, including reduction and oxidation, is 320.09kJ/mol-C_2H_5OH, 121.88kJ/mol-C_2H_5OH lower than that of the reference system

(441.97kJ/mol-C_2H_5OH).

3.3 Power subsystem

Fig.5 (a) and Fig. 5 (b) depict the exergy destruction of the power subsystems, which is mainly caused by inefficiency of turbines and compressor. As shown in Fig. 5, the work output of the gas turbines and steam turbines are indicated by the width of $A_{ed,GT}$ and $A_{ed,ST}$ respectively, and the width of $A_{ea,comp}$ represents the work required for air compression. The exergy destruction of gas turbines and steam turbines is illustrated by the area "1234", while that of the compressor is indicated by the area"1567". It can be seen from Fig. 5 (a) that, the net work output of the turbines of the reference system is 435.37kJ/mol-C_2H_5OH, and the exergy destruction of the power subsystem is 123.55kJ/mol-C_2H_5OH. By contrast, as indicated by Fig. 5 (b), the net work output of the turbines of the new cycle is 525.42kJ/mol-C_2H_5OH, 90.05kJ/mol-C_2H_5OH higher than the reference one. The exergy destruction of the power subsystem of the new cycle is 147.39kJ/mol-C_2H_5OH.

4 RESULTS AND DISCUSSION

4.1 Potential of Reducing Irreversibility in the Combustion Process.

For any combustion process, the exergy destruction of combustion can be expressed as $\Delta EXL=\Delta H_{comb}(A_{ed}-A_{ea})$, where ΔH_{comb} is the combustion heat of fuel, and A_{ed} and A_{ea} are the energy levels of energy donor and acceptor respectively. In a thermal cycle, A_{ea} corresponds to the energy level of turbine inlet temperature (A_{TIT}), and is equal to ($1-T_0/T_{TIT}$). Traditionally, the usual approach to reduce exergy destruction in combustion is achieved by improving the energy level of energy acceptor A_{ea}, i.e. the turbine inlet temperature. However, the possibility of further improvement of A_{TIT} lessens with the increase of TIT (above 1400℃). This results in little potential for decreasing exergy destruction in combustion.

Completely different from the usual approach, exergy destruction in combustion process of the new system is reduced by lowering the energy level of energy acceptor. In the proposed cycle, the chemical exergy of ethanol is released through chemical-looping combustion: an endothermic reaction with recovering low-temperature solar thermal energy and an exothermic reaction at high temperature. Fig.6 depicts the comparison of the energy level degradation of direct combustion and chemical-looping combustion. The curve of A_f depicts the energy level degradation of ethanol direct combustion, while the energy level degradation of Ni oxidation of the chemical-looping combustion process is illustrated by A_{Ni}. It can be seen that, the average energy levels of A_f and A_{Ni} are 1.04 and 0.89 respectively. As a result, when the TIT of 1288°C (A_{TIT}=0.81) is identified, the energy level difference between A_f and A_{TIT} is 0.23, while the value is only 0.07 for that between A_{Ni} and A_{TIT}. Due to this decrease in the energy level difference between energy donor and acceptor, the exergy destruction of Ni oxidation process of the new system is significantly decreased. Although the irreversibility in the reduction of ethanol with Ni gives rise to the exergy destruction, the total exergy destruction of the reaction subsystem is still 121.88kJ/mol-C_2H_5OH lower than that of the direct combustion (442kJ/mol-C_2H_5OH). It leads a reduction of approximately 9 percentage points based on the input exergy of fuel, meaning that about 9% of fuel can be saved through this chemical-looping combustion method.

4.2 Upgrading of energy level of solar thermal energy

Another advantage of integrating solar thermal energy at around 200°C and CLC is that the energy level of the solar thermal energy can be upgraded to high-grade chemical energy associated with the solid fuel Ni, and released as high-temperature thermal energy to produce electricity with a high-efficiency Brayton cycle. However, in most cases using solar thermal energy at around 200°C produces steam to generate electricity through the inefficient Rankine cycle or the bottom portion of a combined cycle; i.e., the solar thermal energy is transferred only to the thermal energy associated with the saturated steam. That is to say, the proposed system can elevate the energy level of solar thermal energy to a high level of chemical energy, unlike other solar hybrid systems using solar thermal energy at around 200°C.

As shown in Fig. 7, in solarized chemical-looping combustion the energy level of solar thermal energy is upgraded from an A_{solar} of 0.43 (corresponding to 200^{o}C) to an A_{Ni} of 0.89 (corresponding to Ni oxidation). Then this upgraded solar thermal energy is eventually released as thermal energy (A_{TIT}=0.81) for the generation of electricity. It should be emphasized that this benefit is attributed to the energy-level degradation from ethanol combustion to Ni oxidation in the chemical-looping combustion, which acts as a “driving force” to upgrade the energy level of solar thermal energy. Thus, in the new system, the work output of the gas turbine increased by nearly 14 percentage points than reference system.

4.3 Advanced Thermodynamic Performance

Figure 8 illustrates the variation in the overall exergy efficiency (η_{ex}) of the system with varying turbine inlet temperature (TIT) and pressure ratio (π). In addition, for the given π, η increases with an increase in TIT. For each TIT, there is a η_{opt} to get maximum exergy efficiency, which is similar to that of the conventional combined cycle, with the η_{opt} at about 13–16 bar. This means that the new system has a similar value of η_{opt} with the conventional combined cycle. The exergy efficiency is expected to be about 57.3% at the pressure ratio of 13 at a gas turbine inlet temperature of 1400°C, which is similar to the combined cycle and is easily achievable.

Ethanol fueled chemical-looping combustion, especially the reduction of NiO with ethanol, is the core technology of the new system. Thus, the exergy efficiency of the system is deeply influenced by the temperature of the reduction reactor. And, figure 9 illustrates the overall exergy efficiency of the system as it varies with the reduction reactor temperature and turbine inlet temperature (TIT). Similar with the conventional cycle, the exergy efficiency increases as TIT increased from 1200^{o}C to 1400^{o}C. It can be seen that its exergy efficiency decreased with the reduction temperature from 150^{o}C to 400^{o}C which might be caused by the mismatch of the temperature between reduction reaction and heat resource.

4.4 Less Energy Penalty for CO_2 Capture

In conventional technology for suppressing environmental impact, it can be easily found that the undesirable substances formed from the upstream process are often removed from the downstream process with various separation processes by dealing with a great amount of exhaust gas and at a high cost of energy consumption [21]. The tendency of the next-generation systems will be toward the elimination of undesirable formation from the upstream process. From this point, it seems that the CLC combustion will be the promising technology to recover CO_2. Thus, in a thermal cycle with a CLC combustion scenario, environmental pollution due to greenhouse gas emissions will be eliminated. Similarly, the product of the reduction reactor in the chemical-looping combustion is also very simple, consisting of only water and CO_2.

Since solar thermal energy is used in the new system, compared with the conventional combine cycle, it can reduce fuel usage with the same work output, leading to a decrease in CO_2 emission, from 0.47 kg/kWh produced by the conventional combined cycle to 0.40 kg/kWh produced by the proposed cycle here(which is 14.9% less). Moreover, efficiency of a power system achieving CO_2 recovery will normally be reduced by about 5-15 percentage, specifically 7 percentage for ethanol-fueled combined cycle (based on the energy consumption of 0.34 kWh/kgCO_2 using chemical absorption [21])

5 PRELIMINARY EXPERIMENT OF ETHANOL-FUELED CHEMICAL-LOOPING COMBUSTION ON THE FIXED BED

As detailed in our previous work, Jin et al have investigated CLC and published some papers on methane fueled CLC, hydrogen fueled CLC and coal gas fueled CLC [22-24]. A series of good reactive and regenerative oxygen carriers, such as $NiO/NiAl_2O_4$ and CoO-NiO/YSZ, have also been developed by them [12-15]. Ethanol fueled chemical-looping combustion is the core technology of the proposed solar-hybrid cycle. To identify the feasibility of the CLC process, preliminary experiments on the reduction reaction between ethanol and NiO were performed on a fixed-bed [24], as shown in figure 10.

In the experiment, the solid looping material of $NiO/NiAl_2O_4$ was prepared by dissolution method, where the weight ratio of the solid reactant NiO to binder of $NiAl_2O_4$ was set at 6:4. Columnar particles (with Φ2mm and 2mm height) were obtained. These particles were dried at 353 K for 30 minutes and calcined in air at 1573 K for 6h. Ethanol was first evaporated, with the flow rate regulated by current pump, and then fed into the reaction unit. The temperature of NiO/ $NiAl_2O_4$, reduced by ethanol vapor, was set at 500°C, and the metal oxide was regenerated in an air atmosphere at 1000℃. It was observed that part of NiO/$NiAl_2O_4$ was reduced which was verified by an X-Ray Diffraction analysis of the solid production, as shown in Fig.11.

Figure 12 shows the cross-sectional photographs by SEM (scanning electron microscope) for the fresh particles (denoted as a) and for the particles after a cycle of reduction at 500°C (denoted as b) and oxidation at 1000°C (denoted as c). The surface of fresh NiO/ $NiAl_2O_4$ particle had compact structure, after reduction reaction, the grain size of fresh NiO/ $NiAl_2O_4$ particle was as fine as 0.3-0.8μm in diameter. After a cycle of reaction, the surface of looping material became coarse and the interface area between gas and solid was enlarged which might be favorable to next reaction. Accordingly, the preliminary experiment verifies the feasibility of this ethanol fueled chemical-looping combustion and shown that the looping material has good reactivity. By further studying on the looping materials which are compatible with this new combustor, we are looking forward to made progress in realizing the technology of ethanol fueled chemical-looping combustion integrating low-grade solar thermochemical process to achieve effective utilization of solar energy.

6 CONCLUSION

A novel solar-hybrid thermal cycle, integrating ethanol fueled chemical-looping combustion with low temperature solar thermal energy has been proposed and investigated with the aid of graphical exergy methodology. In the ethanol fueled chemical-looping combustion, the energy level of ethanol fuel is down to metal fuel of Ni, then the exergy destruction of combustion is greatly reduced compared with direct combustion of ethanol. Additionally, the new cycle can achieve CO_2 separation with low energy requirement. The energy level of the solar thermal energy at 200°C is upgraded during the endothermic reduction process. As a result, the exergy efficiency of new system with TIT of 1288°C would be expected to be as high as 54.4% with CO_2 separation, and lead to a14.9% less CO_2 emission compared to the conventional combined cycle. The current experimental results of the core process preliminarily verified the feasibility of ethanol fueled chemical-looping combustion, and the development of suitable looping materials and the design of reactor for better reactivity between gaseous reactants and solid particles are needed to make this process viable for actual implementation. The proposed new system will provide a new approach for the efficient utilization of middle-and-low temperature solar thermal energy. In addition, it offers a new opportunity for CO_2 capture by synergistic integration of low-grade solar thermal energy with ethanol fueled chemical-looping combustion.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Natural Scientific Foundation of China (No. 50836005 and No. 50976114)

REFERENCES

[1] Lewis N S., 2007, “Toward cost-effective solar energy use,” Science, 315(5813), pp.798—801.

[2] Fletcher, E. A., 2001, “Solarthermal Processing: A Review,” ASME J. Sol. Energy Eng., 123, pp. 63–74.

[3] Tamaura, Y., Wada, Y., Yoshida, T., and Tsuji, M., 1997, “The Coal/Fe_3O_4 System for Mixing of Solar and Fossil Energies,” Energy, 22(2-3), pp. 337–342.

[4] Steinfeld, A., and Palumbo, R., 2001, “Solar Thermochemical Process Technology,” Encyclopedia of Physical Science and Technology, edited by R.A.Meyers, Academic, New York, Vol. 15, pp. 237–256.

[5] Steinfeld, A., Frei, A., Kuhn, P., and Wuillemin, D., 1995, “Solar Thermal Production of Zinc and Syngas VIA Combined ZnO-Reduction and CH_4-Reforming Process,” Int. J. Hydrogen Energy, 20, pp. 793–804.

[6] Steinfeld, A., 1996, “Thermodynamic Analysis of the Co-Production of Zinc and Synthesis Gas Using Solar Process Heat,” Energy, 21, pp. 205–222.

[7] Werder, M., and Steinfeld, A., 2000, “Life Cycle Assessment of the Conventional and Solar Thermal Production of Zinc and Synthesis Gas,” Energy, 25, pp. 395–409.

[8] Tamme, R., Buck, R., Epstein, M., Fisher, U., and Sugarmen, C., 2001, “Solar Upgrading of Fuels for Generation of Electricity,” ASME J. Sol. Energy Eng., 123, pp. 160–163.

[9] Ishida, M., Jin, H., 1994, “A New Advanced Power-Generation System Using Chemical-Looping Combustion,” Energy, 19, pp. 415-422.

[10] Jin, H., Okamoto, T., Ishida, M., 1999, “Development of a Novel Chemical-Looping Combustion: Synthesis of a Solid Looping Material of NiO/NiAl2O4,” Ind. Eng. Chem. Res., 38, pp. 126-132.

[11] Ishida, M., Jin, H., 1996, “A Novel Chemical-Looping Combustor without NOX Formation,” Ind. Eng. Chem. Res., 1996, 35, pp. 2469-2472.

[12] Ishida, M., Jin, H., 1997, “CO_2 Recovery in a Power Plant with Chemical-Looping Combustion,” Energy Convers. Mgmt., 38, suppl., pp. S187-S192.

[13] Jin, H., Okamoto, T., Ishida, M., 1998, “Development of a Novel Chemical-Looping Combustion: Synthesis of a Looping Material with a Double Metal Oxide of CoO-NiO,” Energ. Fuel., 12, pp. 1272-1277.

[14] Hong, H., Jin, H., Ji, J., Wang, Z., Cai, R., 2005, “Solar Thermal Power Cycle With Integration of Methanol Decomposition and middle-temperature solar thermal energy,” Sol. Energy, 78, pp. 49-58.

[15] Hong, H., Jin, H., Liu, B., 2006, “A Novel Solar-Hybrid Gas Turbine Combined Cycle With Inherent CO_2 Separation Using Chemical-Looping Combustion by Solar Heat Source,” ASME J. Sol. Energy Eng., 128, pp. 275-284.

[16] Hong, H., Han, T., Jin, H., 2009, “A Low Temperature Solar Thermochemical Power Plant with CO_2 Recovery Using Methanol-Fueled Chemical Looping Combustion,” Proceedings of the ASME 2009 3rd International Conference of Energy Sustainability, San Francisco, California, USA.

[17] M.J. Montes, A. Aba ´nades, J.M. Martı ´nez-Val, M. Valde ´s. 2009, “Solar multiple optimization for a solar-only thermal power plant, using oil as heat transfer fluid in the parabolic trough collectors,”Solar Energy,83, 2165-2176.

[18] Aldo Steinfeld, Robert Palumbo, 2001, “SOLAR THERMOCHEMICAL PROCESS TECHNOLOGY,” ENCYCLOPEDIA OF PHYSICAL SCIENCE & TECHNOLOGY, R. A. Meyers Ed., Academic Press, Vol. 15, pp. 237-256.

[19] Tammer R, Buck R, Epstein M, et al. Solar Upgrading of Fuels for Generation of Electricity. ASME. J. Sol. Energy Eng., 2001, 123(2): 160-163

[20] Ishida, M., Ji, J., 1999, ‘Graphical Exergy Study on Single Stage Absorption Heat Transformer’, *Appl. Therm. Eng.*, 19, 1191-1206.

[21] Riemer, P., 1996, “Greenhouse Gas Mitigation Technologies, an Overview of the CO_2 Capture, Storage, and Future Activities of the IEA Greenhouse Gas R&D Program,” Energy Convers. Manage., 37(6–8), pp. 665–670.

[22] Jin, H., Ishida, M., 2002, “Reactivity Study on Natural Gas-Fueled Chemical-Looping Combustion by a Fixed Bed Reactor,” Ind. Eng. Chem. Res., 41, pp. 4004-4007.

[23] Jin, H., Ishida, M., 2000, “A Novel Gas Turbine Cycle with Hydrogen-Fueled Chemical-Looping Combustion,” Int. J. Hydrogen Energy, 25, pp. 1209-1215.

[24] Jin, H., Ishida, M., 2004, “A New Type of Coal Gas Fueled Chemical-Looping Combustion,” Fuel, 83, pp. 2411-2417.

TABLE 1 MAIN ASSUMPTION FOR THE SIMULATED SYSTEMS

Item	New system	Reference system
Direct solar radiation (W/m^2)	800	800
Solar thermal energy temperature(^{o}C)	200	-
Optical efficiency (%)	65	65
Pressure of the reduction reactor (bar)	15	-
Turbine inlet temperature of GT1(^{o}C)	1288	1288
Turbine inlet temperature of GT2(^{o}C)	1288	1288
Gas Turbine inlet pressure (bar)	15.00	15.00
Isentropic efficiency of air compressor	0.86	0.86
Isentropic efficiency of gas turbine	0.87	0.87
Isentropic efficiency of steam turbine	0.88	0.88
Pressure loss of HRSG (gas-side) (%)	3	3
Pressure loss of HRSG (gas-side) (%)	10	10
Pinch point in HRSG(^{o}C)	20	20

TABLE 2 COMPARISON OF EXERGY ANALYSIS

Exergy analysis				
Items	The new system		The reference system	
	Exergy (kJ/mol-C_2H_5OH)	Ratio (%)	Exergy (kJ/mol-C_2H_5OH)	Ratio(%)
Ethanol fuel	1354.57	93.7	1354.57	100
Solar thermal energy	92.03	6.3		
Total input exergy	1446.57	100	1354.57	100
Exergy destruction				
Reaction subsystem	320.09	22.13	441.97	32.63
Heat exchanger	42.37	2.93	—	—
HRSG	53.74	3.71	50.01	3.69
Compressor	39.89	2.76	31.82	2.35
Turbine	107.51	7.43	91.73	6.77
Exhaust gas loss	44.70	3.09	36.69	2.71
Other(CO_2+H_2O)	29.32	2.03	—	—
Output exergy (Net power)				
Gas turbine	525.42	36.32	435.37	32.14
Steam turbine	261.80	18.10	251.80	18.59
Total net power	787.23	54.42	687.17	50.73
Sum of Exergy	1450.28	100.26	1359.82	100.39
Exergy efficiency	—	54.42	—	50.73
Thermal efficiency	—	54.40	—	55.72
Net solar-to-electric efficiency	28.6%			

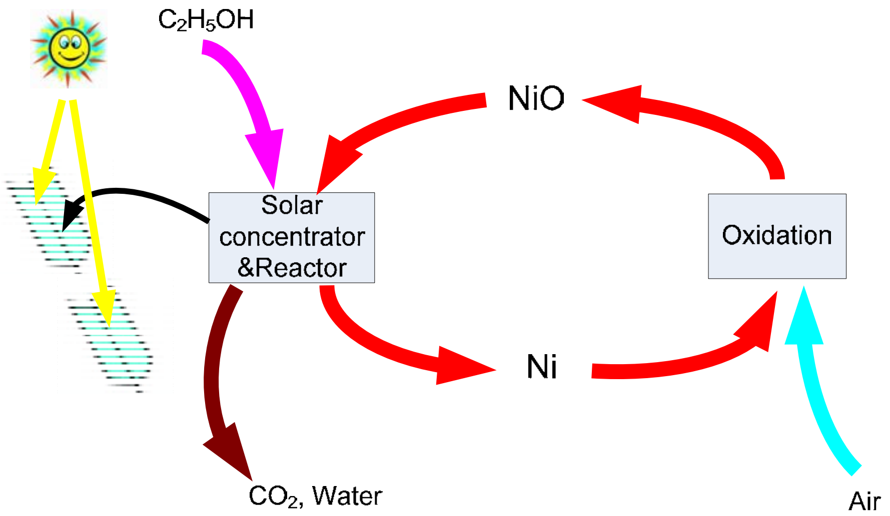


FIG.1. ROUND AND ROUND. In this reactor, hear from concentrated sunlight converts nickel-oxide(NiO) catalyst into metallic nickel (Ni), CO_2 and water. A second step swipes oxygen to restore the catalyst.

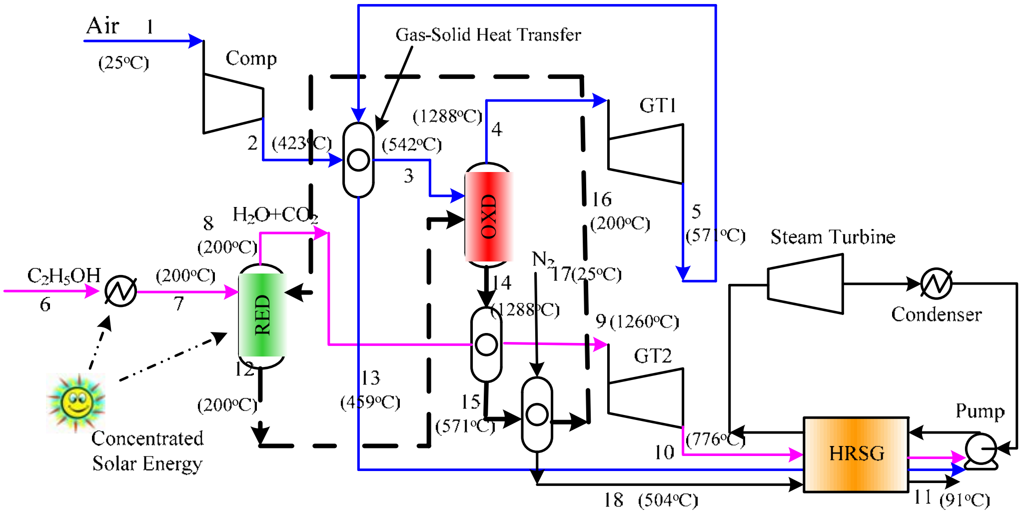


FIG.2 SIMPLIFIED FLOW DIAGRAM FOR SOLAR-HYBRID SYSTEM WITH CLC

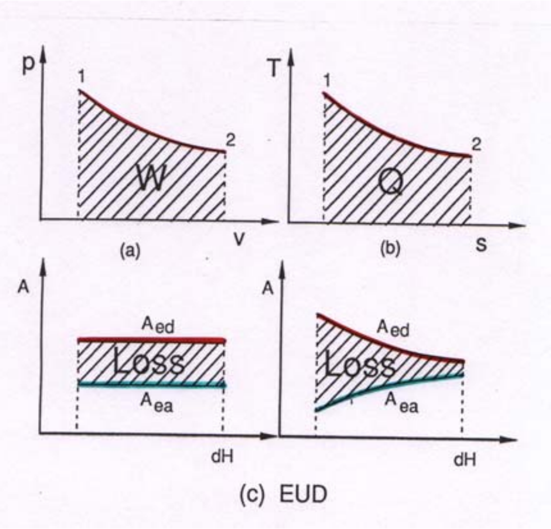


FIG. 3. INDICATOR DIAGRAMS

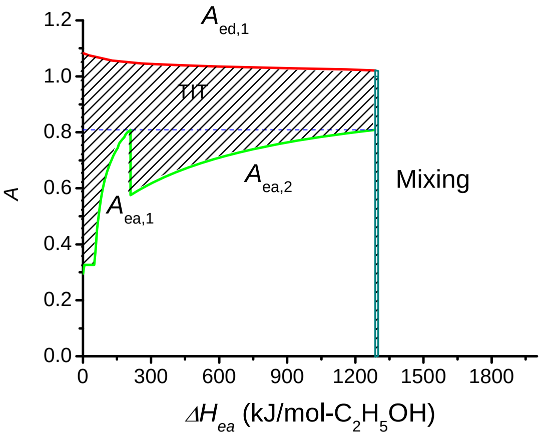


FIG.4 (a) EUD FOR DIRECT COMBUSTION OF ETHANOL

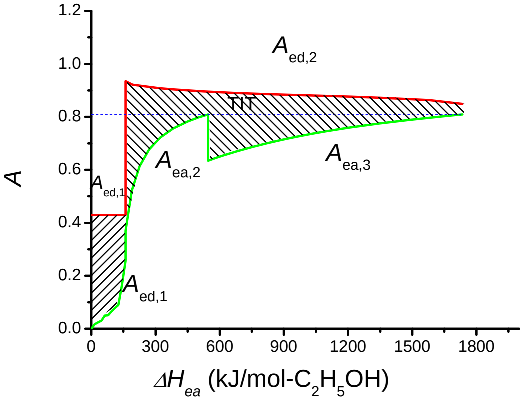


FIG.4 (b) EUD FOR ETHANOL-FUELED CLC

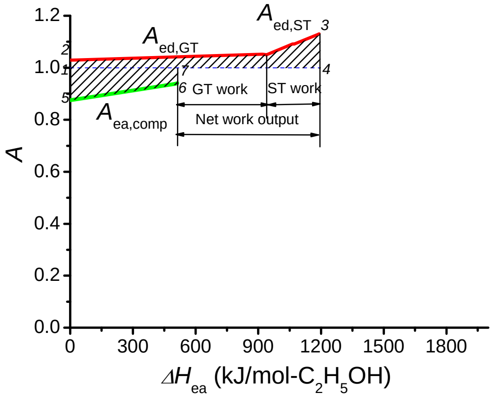


FIG.5 (a) EUD OF POWER SUBSYSTEM OF REFERENCE SYSTEM

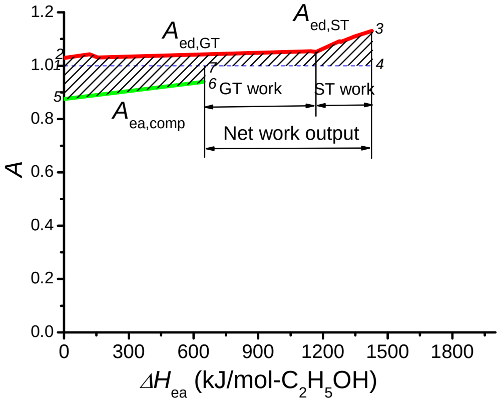


FIG.5 (b) EUD OF POWER SUBSYSTEM OF NEW SYSTEM

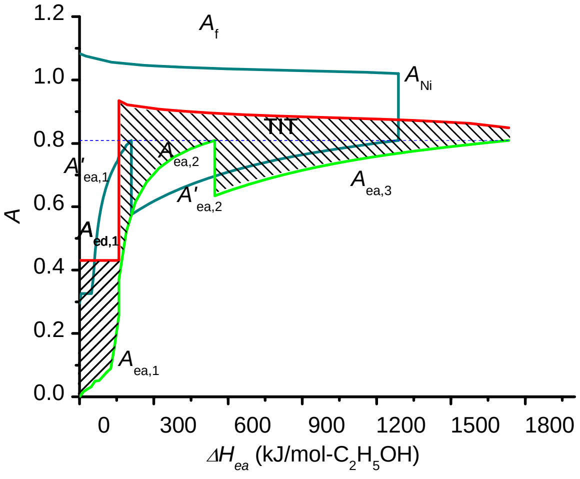


FIG.6. REDUCTION OF ENERGY LEVEL DEGRADATION OF COMBUSTION

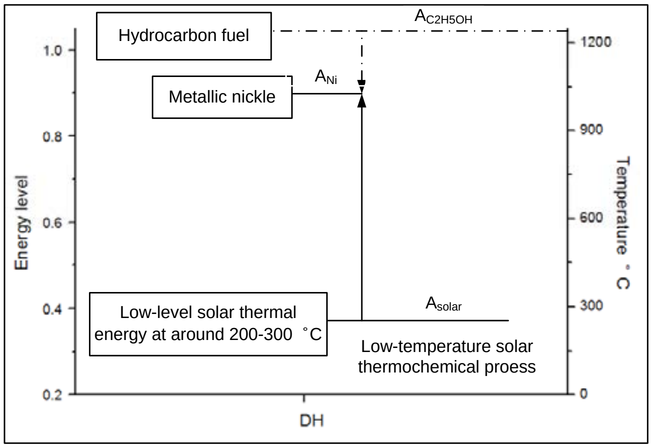


FIG.7. SCHEMATIC OF THE MECHANISM OF THE THERMOCHEMICAL ENERGY CONVERSION INTEGRATING LOW-TEMPERATURE SOLAR THERMAL ENERGY AND ETHANOL FUEL CLC

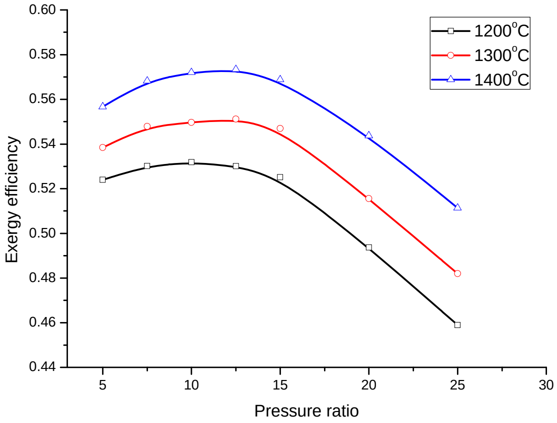


FIG.8. VARIATION OF EXERGY EFFICIENCY WITH TIT AND PRESSURE RATIOII

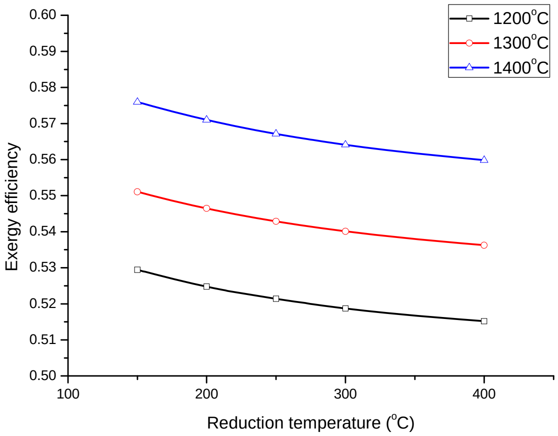
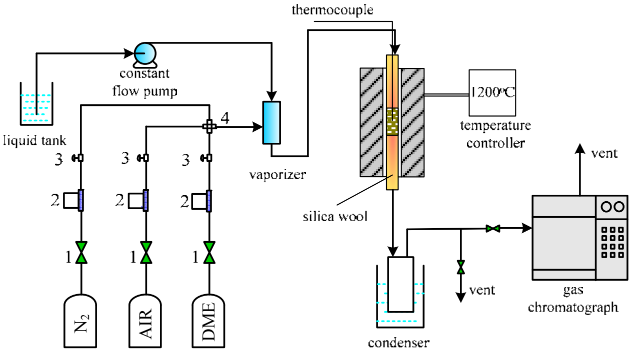


FIG.9 . VARIATION OF EXERGY EFFICIENCY WITH DIFFERENT REDUCTION TEMPERATURE



1, pressure-regulating valve; 2, mass flow controller; 3, stop valve; 4, cross joint

FIG.10. LAYOUT OF THE EXPERIMENT ON THE REDUCTION REACTION OF NiO/Al_2O_3 AND C_2H_5OH

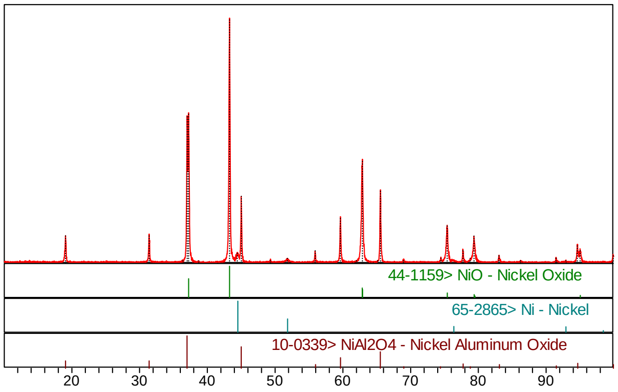


FIG.11. X-RAY DIFFRACTION ANALYSIS OF REDUCTION

PRODUCTION BETWEEN NIO/ NIAL$_2$O$_4$ AND C$_2$H$_5$OH

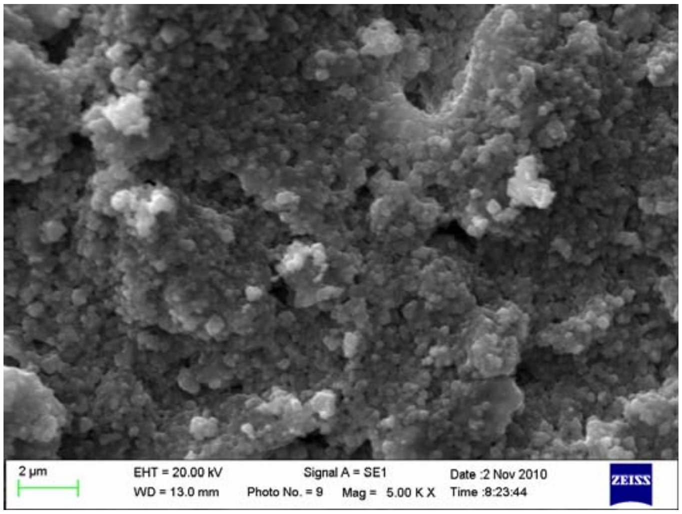


FIG.12 (a) SEM PHOTOS OF FRESH NIO/ NIAL$_2$O$_4$

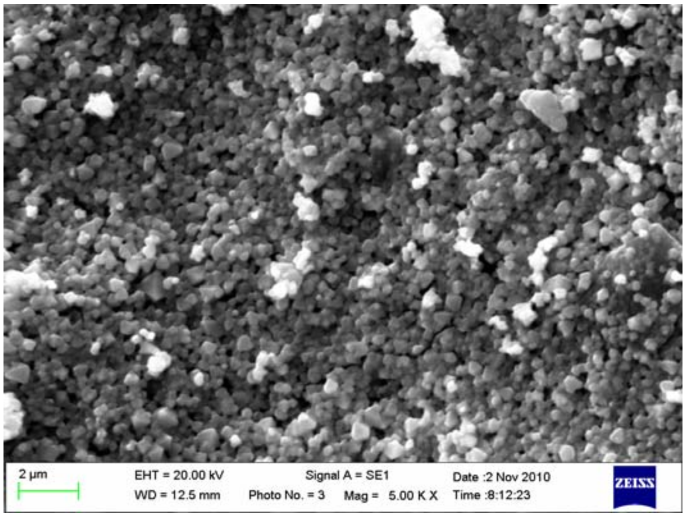


FIG.12 (b) SEM PHOTOS OF NIO/ NIAL$_2$O$_4$ AFTER REDUCTION AT 500^{o}C

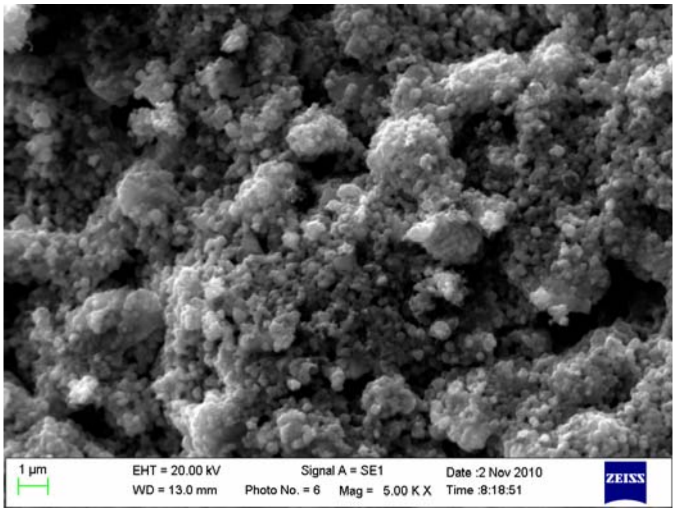


FIG.12 (c) SEM PHOTOS OF NIO/ NIAL$_2$O$_4$ AFTER ONE CYCLE