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Thermodynamic analysis of solar-assisted hybrid power generation systems integrated with thermochemical fuel conversion

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ABSTRACT

Solar-assisted hybrid power generation systems integrated with thermochemical fuel conversion are of increasing interest because they offer efficient use of lower temperature solar heat, with the important associated advantages of lower emissions, reduction of use of depletable fuels, production of easily storable fuel to alleviate the variability of solar heat, and relatively low cost of the use of lower temperature solar components. This paper examines thermodynamic features and performance of thermochemical hybridization of power generation systems, and demonstrates it for two previously proposed and analyzed specific systems, SOLRGT that incorporates reforming of methane, and SOLRMCC that incorporates reforming of methanol, both of which using lower temperature solar heat (at ~220 °C) to help reform the fuel input to syngas, which is then burned for power generation. This analysis resulted in an equation for the power system performance in terms of the *energy level* (exergy to enthalpy change ratio) of the syngas produced by the thermochemical process. It was found that the solar-to-electricity efficiency is higher by up to 42% in the investigated cases if lower temperature solar heat is used in the thermochemical hybrid systems, compared to using the solar-only power generation systems with the same turbine inlet temperature.

1. Introduction

Most thermal power generation systems (e.g. fossil fuel, nuclear, solar, geothermal) use a single source of heat at a single temperature, and also use that heat source directly as heat. In cases where the cost of the heat is related to the temperature, such as with solar heat collection equipment, or when the temperature of the heat source is limited by operational considerations, such as in nuclear reactors, or when the available temperature is well below the material endurance temperature, such as in geothermal heat sources, or when it is desired to employ renewable or other types of energy that reduces global warming gas emissions or/and reduces use of depletable fuels, or when waste heat at appropriate temperatures and price is available, such as in compounded internal combustion engines, it was found that gains in efficiency and reduction of emissions and cost could be achieved by power systems using multiple heat sources of different temperatures, which are called here “hybrid” systems.

Early work on hybrid power cycles was done by Lior and coworkers [1–5] who have analyzed and developed hybrid solar-powered/fuel assisted steam cycles and performed experiments with one of them (22.4 kW output), a concept similar to the one that was later (in the 1980-s) used by the Luz company for the construction and successful operation of 9 solar-thermal power plants (SEGS) generating about 354 MWe (net) in southern California [6–8], that still operate competitively. The concept is successful because it uses solar energy at the lower temperature level, where it is more economical, and augments it by smaller amount of heat from fuel combustion to: (1) raise the cycle temperature and thus efficiency, and (2) allow fuel heat backup when solar energy is not sufficiently available, without having to increase the number of collectors and thermal storage capacity. Furthermore, proper configuration of the systems' heat donors and receivers offers a closer match between their temperatures (smaller temperature differences between donors and receivers) and thus lower exergy losses.

Different from the typical thermal hybrid systems that may involve chemical reactions in the heat addition process only, if fuel combustion is used, thermochemical hybrid systems are designed to include chemical reactions, typically to convert some

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Nomenclature

AHS	Additional heat source
b	Specific exergy [kJ/kg]
B	Exergy [kJ]
H	Enthalpy [kJ]
LHV	Lower heating value [kJ/kg]
Q	Heat transfer [kJ]
$\dot{Q}$	Heat transfer rate [kW]
T	Temperature [K]
T_0	Ambient temperature [K]
X_{sol}	Solar share (eq. (52))
$\dot{W}$	Power [kW]

Greek symbols

φ	Weighting factor (eq. (37))
η	Energy efficiency
$\mathit{\Lambda}$	Energy level (eq. (7))
$\mathit{\Delta}$	Difference

Subscripts and superscripts

0	Reference (non-hybrid, single heat source) system
aux	Auxiliary heat
d	Destruction
h	Heat, hybrid system
ea	Energy acceptor
ed	Energy donor
ex	External heat input to the reformer
f	Fuel
LT	Lower temperature
HT	Higher temperature
max	Maximum
rec	Reaction
ref	Reference
s	Steam
se	Solar-to-electricity
sg	Steam generation heat
sol	Solar
ss	Solar surface
syn	Syngas
tr	Transferred heat
w	Water

hydrocarbon to readily-usable fuel, altogether to result in a more efficient and less polluting power generation system. In this type of system, lower temperature heat, such as solar, geothermal, or waste, is converted by such chemical reactions to the chemical exergy of the ultimately-combusted fuel (such as syngas). Compared with thermal hybridization, thermochemical hybridization can have also the advantage that it can allow conversion of the exergy of intermittent heat sources (such as solar) to much higher fuel chemical exergy that is therefore much easier to store and transport than the energy/exergy of such input heat sources. Furthermore, low/mid temperature solar heat (~200 °C) is high enough to be used by a syngas-producing reforming process, thus potentially reducing the total cost relative to conventional solar thermal power plants that necessarily use more expensive solar collection equipment due to their higher solar temperature. It was often stated in the literature that the quality of the low temperature input is "upgraded" by such thermochemical processes. We note that this statement is correct for some types of heat sources, such as geothermal or waste heat, but its correctness for solar heat sources depends on the solar exergy definitions as explained in section 2.1.3.

2. Thermochemical hybrid power systems introduction

2.1. Thermochemical hybrid system using methane as fuel

Comprehensive work has been done on thermochemical hybrid power systems and many have been proposed and analyzed. Two case studies are shown in this paper about how this type of systems works and what advantages they have. "Solar thermochemical upgrading" is explained and discussed, followed by more general thermodynamic analysis of thermochemical hybrid systems. The first case analyzed in this paper focuses on a novel Chemically-Recuperated Gas-Turbine Power Generation (SOLRGT) System proposed and described in [9–11].

2.1.1. System introduction

The flow diagram of SOLRGT is shown in Fig. 1, and all used operating parameters, such as temperature, pressure and chemical parameters, are from [9]. It can be seen from the flow diagram that solar heat collected by a parabolic concentrating solar collection equipment at 200–250 °C is used to generate the steam needed for the following reforming reaction, thereby converting the solar heat to that of the steam internal energy (stream 6 in Fig. 1), which is then converted to the chemical exergy of the syngas generated in the reformer, by using that steam, methane, and exhaust heat from the system gas turbine. The fuel conversion process is by the reactions:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \Delta H = 206.11\ \mathrm{kJ/mol} \tag{1}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \Delta H = -41.17\ \mathrm{kJ/mol} \tag{2}$$

Reaction (1) is the methane reforming process, which is endothermic, with that heat provided by the gas turbine exhaust gas (stream 16 in Fig. 1), at about 600 °C. At this temperature, 20–50% conversion of methane (stream 10) is realizable and higher conversion is achieved with more steam (stream 6), higher temperature and lower pressure in the reformer. Reaction (2) is a shift reaction, which is exothermic and heat released from it partially provides the heat needed for the methane reforming process of eq. (1), in addition to the heat from gas turbine exhaust heat.

The produced hydrogen-rich syngas (about 19% H_2, 8% CH_4, 68% H_2O, 4% CO_2 and <1% CO when the steam/methane mole ratio is 6.1) from the reformer is then burned in the combustor with the compressed air recuperated by the reformer exhaust gas. As eqs. (1) and (2) show, both reactions are bi-directional, and the reactants composition shows that they are not complete (not all of the methane is converted). The high temperature and pressure (1308 °C, 14.55 bar) produced syngas is then burned to generate power by the turbine that drives an electricity generator.

To increase the efficiency of the system, internal heat recovery is incorporated, in cascade, as shown in Fig. 2. The high temperature gas turbine exhaust gas (stream 16 in Fig. 1) is first used to provide the heat needed in the reformer for the methane reforming reaction. The exhaust heat from the reformer (stream 17) is then used to preheat the pressurized air (stream 4) from the compressor. At last,

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