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Research Paper

A thermodynamic analysis and economic evaluation of an integrated lignite upgrading and power generation system

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HIGHLIGHTS

- The proposed system efficiently produces exportable upgraded coal and electricity.
- Energy efficiency of the proposed highly-integrated system reaches 79.6%.
- Equivalent energy conversion ratio for lignite upgrading soars to 100.8%.
- Produced upgraded coal is more economical for energy transmission in China.

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ABSTRACT

Effective upgrading for efficient utilisation of lignite is of great significance for countries that highly dependent on coal for power generation. This work proposed and evaluated an integrated system for lignite upgrading and utilisation using pre-drying, low-temperature oxidative pyrolysis (LTOP) and power generation, beneficially converting lignite into an exportable thermal coal while generating power locally. In the proposed system, LTOP was adopted to upgrade lignite, and the pre-drying process would reduce the moisture content of lignite prior to LTOP and boiler using steam bleeds from the conjunct steam turbine, saving a part of reaction heat consumed by moisture evaporation. The energy of raw syngas produced in LTOP process was efficiently utilised by co-combusting with a portion of pre-dried lignite in boiler, and the sensible heat of upgraded coal was recovered by preheating the feed/condensate water of steam turbine unit. With the developed models and process simulation, the mass and energy balance of the proposed integrated system for upgrading Zhundong lignite (ZD) in conjunction with a 600 MW supercritical electric power plant were determined. Detailed thermodynamic analysis showed that the proposed system produces annually 1.66 million tonnes of exportable upgraded coal with lower heating value (LHV) of 29.45 MJ/kg, as well as 3118.5 GWh electricity, with overall energy efficiency at 79.6% and the ratio of produced electricity over the energy of upgrade coal product at 22.9%. As a considerable technical route for long-distance energy transportation, economics of deploying the proposed systems in north-western China and exporting the upgraded coal (TR-I) to the eastern seaboard over a distance of 3000 km was quantified, and compared with the option of adopting ultra-high voltage (UHV) electric power transmission (TR-II). It was shown that, the overall CAPEX of TR-I is ~59% less than that of TR-II and the gross cost of electricity (COE) of TR-I is ₵5.20/kWh, also much lower than that of the TR-II.

1. Introduction

Lignite, as one kind of low-rank coal, accounts for ~45% of the world's coal resources and is expected to play an increasingly important role in future power generation in many countries and regions, such as China, USA and south-eastern Asia [1,2]. In China, lignite is increasingly used for power generation [3,4] to meet the soaring energy demand as the high quality bituminous thermal coal reserves deplete rapidly. Hence, how to efficiently and environmentally-responsibly utilise lignite for power generation is of great significance.

Lignite as a primary energy source generally suffers from three inherent challenges [5]: (1) high moisture, and therefore relatively low heating value; (2) highly reactive nature due to rich surface oxygenated functional groups, and therefore high spontaneous combustion

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Nomenclature

Abbreviation

LTOP	low-temperature oxidative pyrolysis
ZD	Zhundong lignite
LHV	lower heating value (MJ/kg)
TR-I	technical route one
TR-II	technical route two
UHV	ultra-high voltage
CRF	capital recovery factor
COE	cost of electricity ($/kWh)
AC	alternating Current
DC	direct Current
HPST	high-pressure steam turbine
IPST	Intermediate-pressure steam turbine
LPST	low-pressure steam turbine
RH	regenerative heater
DEA	deaerator

Symbols

r	average heat required for moisture evaporation (kJ/kg)
c	average specific heat capacity [kJ/(kg·K)]
t	temperature (°C)
M	moisture content (wt%)
α	mass flow ratio for dried lignite fed into the oxidative pyrolyzer over the overall produced pre-dried coal
ξ	loss rate (%)
W	electric power output (kW)
U	equivalent lignite upgrade ratio
p	price ($/unit)
S	scale
F	scale factor
b	coal consumption rate (g/kWh)
h	annual full-load operating hours (hours)
Cap	capacity of a generation unit (kW)
i	discount rate (%)
N	life span of equipment (year)
l	transmission distance (km)

Subscripts

rl	raw lignite
pl	pre-dried lignite
w	water
s	steam
ar	as received basis
d	dry basis
pl	pre-dried lignite
sp	steam pre-dryer
uc	upgraded coal
rs	raw syngas
rf	recycled flue gas
op	oxidative pyrolyzer
m	moisture
v	volatiles
o	oxidation
f	flue gas
fw	feed water
aux	auxiliary
en	energy
eq	equivalent
a	average
b	boiler
t-e	steam turbine – electricity generator system
con	conventional power plant
pro	proposed system
t	transmission/transportation
c	coal
e	electricity
oper	operation

potential; and (3) high alkali content, and therefore severe ash deposition problems in furnaces. The relatively high moisture content is often considered as a major issue related to the efficient use of lignite for power generation. In addition, the first two factors make lignite uneconomical and even dangerous to transport over long distances to where energy services are required. Unfortunately, lignite is often found in remote regions far from the energy consuming centres. For example, Zhundong lignite (ZD) deposit with ~400 billion tonnes in reserve has recently been found and commercially exploited, and may serve to provide China with a secure energy source for many decades to come [6]. However, ZD or the energy liberated from it, would have to travel some 3000–5000 km from Xinjiang, far northwest of China, to eastern China where the energy demand is high. Therefore, it is necessary to upgrade lignite, such as ZD, to make it more efficient for power generation as well as suitable for long-distance transportation.

Low-temperature oxidative pyrolysis (LTOP) is a considerable process for lignite upgrading [7–9], in which coal particles are allowed to react with a small amount of oxygen and a mild thermal oxidation reaction will occur. The active oxygenated functional groups will be cracked and part of the volatile matter as well as moisture will be correspondingly released and removed. For the influence of the moisture on the lignite utilisation efficiency, Xu et al. [10] concluded that, as 0.1 kg moisture was removed per kg raw coal, the LHV of the dried coal could increase by 12–13% and net efficiency of power generation using the upgraded coal could increase by 0.6–0.9%-point. For the oxidation of the active oxygen-containing functional groups, Guan et al. [11] found that the oxygenated functional groups would gradually crack, releasing CO_2 and H_2O during the pyrolysis of Huolinghe lignite and Xiaolongtan lignite at 150–450 °C; meanwhile, the trend of oxygen absorption capacity of the treated lignite would decrease with increasing temperature for pyrolysis. Ryuichi Kaji et al. [12] investigated the influence of the pyrolysis temperature on the water-absorption properties and showed that the water-holding capacity would decrease by two-thirds under 400 °C. O.I. Ogunsola et al. [13] carried out the pyrolysis experiment of the two kinds of the western Canadian coals at varying temperatures in the range of 200–400 °C, and found that the spontaneous risk was significantly decreased with the pyrolysis temperature increase, due to the fact that a large part of the surface oxygenated functional groups had been destroyed during pyrolysis. Yang et al. [14] investigated the pyrolysis characteristics of several kinds of Chinese lignite and found that the optimal operation temperature is ~350 °C for the lignite upgrading considering both the quality of products and the economic expenditure. It seems that through using the LTOP operated at 350–500 °C can increase the energy density of lignite by moisture remove and is able to destroy the pore structure and oxygenated functional groups, which makes them exportable and efficient for utilisation.

Different from the conventional pyrolysis or gasification processes operating at high temperatures, only part of volatile matter is released during the LTOP, and the syngas discharged from the LTOP naturally contains a large amount of moisture and non-combustible gases, such as CO_2, which makes it difficult to achieve a steady flame if combusted on its own [15,16]. While, the syngas still contains a certain amount of low-density chemical energy and sensible heat, and thus, how to utilise