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Thermodynamic analysis of solar energy integrated underground coal gasification in the context of cleaner fossil power generation

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ABSTRACT

Underground coal gasification (UCG) is an *in-situ* physico-chemical process for the conversion of deep coal resources into useful product gas. The UCG process is inherently a clean coal technology avoiding several difficulties of conventional coal mining process. However, it is a complex *in-situ* phenomenon depending on site-specific geological parameters. Energy loss occurs in a UCG process due to water influx, underground cavity pressure drop, gas loss to the surrounding strata and high temperature gasifying medium, which are major challenges of UCG operation. These losses can be compensated if UCG is integrated with solar energy, which is a renewable and a cleaner source of energy. In the present study, two types of low pressure UCG based power plants are conceptualised using solar energy – (i) a conventional steam turbine cycle consisting of a high pressure, a medium pressure and a low pressure turbine and (ii) a gas turbine cycle with supercritical carbon dioxide (sCO_2) as a working fluid operating in a combined cycle power plant system. The scope of integration of solar power on the UCG based power plant systems is discussed for cleaner energy production. A detailed thermodynamic analysis is carried out to estimate the thermal efficiency of both cycles for cases with and without the integration of solar energy. A net thermal efficiency of the solar-UCG based steam turbine cycle is found as 28.2% with carbon capture and storage (CCS). The solar-UCG based sCO_2 gas turbine cycle shows a high net thermal efficiency of 32.9% with CCS, which is 4% higher than the respective system without having solar energy utilization.

1. Introduction

Coal is a major source of energy in the countries such as India, China, Australia and USA, where it is found in abundance. In worldwide, 6185 million tons (Mt) of coal and 1042 Mt of brown coal are produced using traditional surface mining methods [1]. India has an estimate of 253 billion tons of coal resources against 728 million tons of crude oil and 686 billion cubic metres of natural gas [2]. This makes coal an indispensable source of energy as well as chemical feedstock. Out of this stock, only one sixth is economically accessible [3]. The greenhouse gases such as CO_2, NO_x, CH_4 generated on coal mining and combustion are detrimental to human health as well as environment. Therefore, the environmental cost of utilization of coal energy under clean mode is expensive. In India, the emissions due to the usage of fossil fuels are found to be increasing at an alarming annual growth rate of 5%. It is high in itself but still it is 4.5 times lesser than USA and 3.7 times lesser than China [4]. Thus, the major challenge of the coal industries is the capture and storage of pollutants for creating a clean environment. Clean coal technologies capture CO_2, sulphur, SO_x and NO_x in various stages of operation – before or after burning.

The development of clean and energy efficient integrated system is essential for the implementation of clean environment. The utilization of fossil energy sources such as coal and oil reserves emits a larger proportion of CO_2 into atmosphere without treatment [5]. These carbon gases accumulate and create global warming, which is harmful and dangerous to living beings. The integration of carbon capture and storage (CCS) with the existing power plant system is expensive [6]. Therefore, it is crucial to investigate a number of economical ways for cleaner energy production with the available energy sources. Integration of renewable energy sources with the existing conventional energy technologies is a promising option for a sustained clean energy production and low carbon emission controlling strategies. Andric et al. [7] performed carbon footprint analysis and energy analysis for the co-firing of biomass with coal and, their results show that 11–25% of CO_2 emissions are reduced due to the addition of 20% biomass with coal fired combustion mixture. Similarly, solar energy is the other renewable energy and can be appropriately integrated with non-renewable energy sources such as coal for the power production; it may reduce majorly the accumulation

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of greenhouse gases in the atmosphere and paves a way for cleaner energy production. In this context, the present study investigates the feasibility of integration of underground coal gasification (UCG) with solar energy for cleaner and efficient energy production.

Underground coal gasification (UCG) emerges to be a promising option for converting deep coal reserves into fuel gas, which could be used for power generation or manufacture of chemicals. It is a clean coal technology, which eliminates several conventional process difficulties [2]. The UCG process is more intricate and its performance index depends on the geological characteristics of the specific site. There is a limited set of operating parameters such as operating pressure, gas flow rate, gas composition at the injection point, temperature etc. for the performance of UCG [8]. The idea of using UCG gas for electricity production has been in practice for a long period. In Angren–Uzbekistan, a UCG plant has been in operation since 1961 [9] and the gas produced in the UCG plant is supplied to Angren power station. A UCG gas production facility is developed successfully at Chinchilla, Australia and a high pressure product gas (10 bar) with average calorific value of 5 MJ/m^3 is produced [10]. This gas is supplied to a gas turbine combined cycle plant for power generation. A life cycle study of this UCG integrated plant claims 25% less CO_2 emissions than the most highly efficient coal power plants of the region. This delineates the importance of UCG as a valuable and less polluting alternative to the conventional coal and natural gas based power plants.

A number of studies have been carried out to find out the efficacy of UCG gas in power generation. Nakaten et al. [11] focussed on calculating the cost of electricity by using UCG gas in a gas turbine with carbon capture and storage (CCS). Their results show that electricity cost of 71.67 Euro/MW h was estimated out of which the CCS exacted 20.5%. Prabu and Jayanti [12] studied the viability of UCG with its integration to solid oxide fuel cell (SOFC) and net thermal efficiency comparisons were made with a conventional steam cycle using oxy fuel combustion. A net thermal efficiency of 32.33% was observed for low pressure UCG integrated SOFC cycle while 25.94% was estimated for steam cycle operation. Energy losses may occur in a coal seam and it reduces the overall efficiency of the UCG based power systems. The major energy losses of UCG process include water influx, pressure drop in the UCG cavity, gas loss to the surrounding burden and the usage of high temperature gasifying medium. The water influx and gas loss can be minimized by operating the UCG process under optimum pressure in an underground cavity. The compressed injection gas maintains the pressure of gasification chamber slightly higher than the surrounding and thus inhibits the leakage of surrounding water into the coal seams. Water influx into coal seams leads to unnecessary loss of thermal energy of coal and reduction in gasification efficiency [13]. Pressure drop in underground cavity leads to the generation of low pressure UCG product gas and these product gases can be integrated only to the steam turbine power generation system. Persichilli et al. [14] have discussed the reason for the decreased efficiency of steam cycles. The phenomenon of pinch point occurs while phase change from water into steam at constant temperature. This limits the maximum achievable fluid temperature and consequently the thermal efficiency of steam cycles. In other route, the low pressure UCG gas can be effectively converted into electric power using a gas turbine with supercritical CO_2 (sCO_2) as a working fluid operating in a combined cycle operation. The sCO_2 is a single phase fluid allowing for continuous temperature increase from the same heat source and achieves a high efficiency. The same property also entails the advantage of simple, single pressure exhaust heat exchanger design with low gas side pressure drop. In addition, the critical temperature of CO_2 is 31°C, which is close to the environment temperature having an added advantage of high efficiency of the cycle [15]. Further, the energy penalty due to acid gas removal in a gas purification unit of gas turbine system is avoided in a sCO_2 turbine system. Sulphur impurities are removed in a post combustion unit by the gypsum production process with a minimal energy penalty.

Other constraint in a UCG process is the transportation of high temperature gasifying agent such as steam to deep coal seam. The use of the gasification agent steam in UCG under appropriate conditions may raise the calorific value of the product gas. There should be an optimized ratio of steam to oxygen for the efficient production of syngas [16]. The steam production and transportation to deep coal seams are expensive. These energy losses are compensated on suitably integrating the UCG with renewable energy sources. One such readily available source is the solar energy. The combination of solar energy with UCG operation may increase the efficiency of power plant system. In solar energy integrated system, the net thermal efficiency could be improved by preheating and reheating the working fluid using solar heat. Extensive research has been carried out by Kalogirou [17] in the field of solar energy and proven technologies for steam generation using parabolic trough collectors (PTC) have been found. It has been found that the operation of solar thermal power plants become a reality with thermal energy storage concept. The thermal storage system uses phase change materials storage for evaporation purposes and molten salt storage for preheating and superheating. The traditional choice of phase change material as heat transfer fluid (HTF) is synthetic oil. Superheated steam is used to exchange heat with HTF and molten salt during charging from solar field [18]. This system provides operational flexibility to the continuous process. The production and use of superheated steam at 535 °C using solar energy lead to a consequent increase in net thermal efficiency of the power plant system [18]. The solar power can also be efficiently used in fuel (gasoline) production using Fischer–Tropsch synthesis and it is reported that the use of solar power reduces the specific carbon emissions by 39% [19]. Therefore, the integration of solar system to UCG can efficiently increase the thermal efficiency as well as reduce the carbon emission.

In the light of these benefits, UCG power plant simulations have been carried out with and without solar energy for the two cycles such as (i) conventional steam turbine cycle and (ii) sCO_2 turbine cycle. In the present study, a low pressure UCG system has been proposed and the scope of effective production of electricity using solar energy is discussed. The solar energy is used in providing a compressed high temperature steam to underground coal gasification chamber. In the steam cycle operation, the solar energy has been used in preheating of water before sending it to combustor/boiler and for preheating of inlet steam of the low pressure turbine. A similar use of solar energy has been made in sCO_2 gas turbine cycle. Fig. 1 shows the schematic representation of the proposed system in the present study. The sCO_2 is preheated before sending it to exhaust heat exchanger using solar collectors. The results of both steam turbine and gas turbine cycle without solar integration have been optimistic giving the average efficiencies at par with conventional coal based power generation systems. The inclusion of solar energy in these cycles leads to 3–4% rise in the net thermal efficiency.

2. Plant description

2.1. Reference data selection

Extensive studies on UCG were carried out by Lawrence Livermore National Laboratory (LLNL) at thirteen different sites of USA for accessing its potential coal resources as a viable commercial source of energy production during mid and late 1970s [20]. In the present study, the UCG data of Hoe Creek site has been used