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Parametric analysis and assessment of a coal gasification plant for hydrogen production

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ABSTRACT

The purpose of this paper is to conduct a parametric study to show the best steam to carbon ratio that produces the maximum system performance of an integrated gasifier for hydrogen production. The study focuses on the energy and exergetic efficiency of the system and hydrogen production. The work is completed using computer simulation models in Engineering Equation Solver software package. This software is used for its extensive thermodynamic properties library. An equilibrium based model is used to determine the performance of the system. The data is presented in graphs which show the chemical composition in molar fractions of the syngas, the overall energy and exergy efficiency of the system, and the hydrogen production rates. A study of these parameters is conducted by varying the steam to carbon ratio entering the gasifier and the ambient temperature. It is observed that the higher the steam to carbon ratio that is achieved the more hydrogen and more power the plant is able to produce. Because of this, the exergy and energy efficiency of the system increases as the steam to carbon ratio increases as well. It is also observed that the system favors a lower ambient temperature for maximum exergy efficiency and hydrogen production.

1. Introduction

It is a well-known fact that the average temperature of the Earth has been fluctuating for millions of years before the arrival of the modern day human. Only in the last century we are seeing some of the fastest increases in the Earth's temperature ever recorded in history. It is the belief that the reason for this increase in temperature is due to human interactions with the environment. The name for this effect is global warming [1].

Ever since the industrial revolution began, there has been an exponential increase of factories, power plants and motor vehicles on the Earth. These technologies all consume an immense amount of fossil fuels. Consumption of fossil fuels usually means the burning, or combustion of typically oil or coal. This process produces large amounts of thermal energy, but at the same time it produces a large amount of greenhouse gasses. Greenhouse gasses consist of carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur oxides (SO_x). These gasses accumulate in the Earth's atmosphere which creates a gaseous blanket which traps thermal energy from leaving the Earth. This blanket is one of the major reasons why we have global warming.

The Earth receives radiation from the sun which provides energy for all life on earth, and also to keep the Earth at a

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temperature where life can exist. In the past, more of that energy was able to escape back into space, but in the post industrial revolution era this is not the case. The greenhouse gas blanket is trapping a lot more of this thermal energy and is contributing to the rapid increase in the Earth's average temperature. This is known as the greenhouse effect.

Signs of global warming can be seen in our recent history. The warmest year that has ever been recorded was in 1998, and the second warmest was in 2005 [1]. Another sign is from the recent analysis of ice cores which show the highest concentration of carbon dioxide and methane dating back 420,000 years ago [1]. Arctic sea ice is also seeing rapid shrinking [1].

The increase of greenhouse gases on Earth is nearly impossible to stop. We have many developing nations and also first world nations who burn incredible amounts of fossil fuels every day. There seems to be no stopping the usage of fossil fuels. Our livelihood depends on these fossil fuels to power our homes, fertilize our produce, transportation, advance our scientific understanding of the world etc. As long as we continue this way of life on Earth, there seems to be no stopping the burning of fossil fuels anytime soon.

It is certain that fossil fuels are here to stay, but that does not mean that humans have to continue using it the way we have for over a hundred years. There have been recent development in cleaner fossil fuel combustion technologies which range from the everyday transport vehicle to enormous power plants. Cleaner combustion technologies are able to have higher conversion efficiency and are able to trap a lot of the harmful greenhouse gas emissions from entering the Earth's atmosphere. One such technology this study focuses on is coal gasification.

Coal gasification is a chemical process in which solid coal, high pressure and high temperature steam and oxygen are reacted to form a synthetic gaseous mixture of hydrocarbons which can be used as a gaseous fuel, or can be further refined to produce hydrogen gas. The coal gas mixture is typically carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and water vapor (H_2O) [2–5]. This process requires more steps than the conventional method of straight air and coal combustion, but it is a lot cleaner for the environment. During the gasification process, all of the useful molecules which produce energy when burned are separated from the unwanted parts of the coal such as soot, tar, and ash. Therefore, this process is much cleaner than burning coal. The emissions are also collected and controlled in the gasification process through carbon capturing and acid removal units.

This technology has been in existence for over 50 years [2]. Its popularity has only been recently developed due to the global warming issue and greater interest for the environmental sustainability. Governments around the world are experimenting with different methods to reduce their greenhouse gas emissions and a lot of them are taking a look at coal gasification as the solution. In the future, it is quite possible to see a lot more coal gasification plants being built because they are much cleaner and conforms to current environmental protocols, policies, and treaties.

There have been many studies performed on gasification technologies. There are numerous articles, publications, textbooks etc., which cover a wide variety of topics relating to gasification and gasification technologies. This section discusses some of those studies that have a varying degree of relevance to the main topic of this paper. Going through this material greatly improves the understanding of the gasification process overall.

Studies have shown that implementing an IGHP system for cogeneration purposes greatly increase the efficiency of the overall system. Many researchers e.g., [6,8,10,14] have investigated such technologies and have studied them extensively. The basic concept behind a combined heat and gasification system is the use of the waste heat from a gas power cycle for heating the gasification process itself. Though the temperatures of most flue gases are not sufficient enough for the temperatures of the gasification reaction, it is used to preheat certain fluids. Air and steam may be preheated by these flue gases.

There have been many studies that focused on using biomass as the gasification fuel. Using different types of fuels yields different efficiencies. This concept is seen throughout [4,5,12,15–17]. The analysis of carbon based materials used for gasification is quite complex and often times many assumptions are made during the calculations. Comparing all the before mentioned work it is clear that coal has highest energy yield in terms of gasification syngas and/or hydrogen production. This is because coal is a material with some of the highest carbon content.

Carbon capturing studies have been performed to understand and improve the methods of carbon capturing for gasification processes. Such studies are seen in Refs. [9,11]. Although not directly related to the main topic of this study, it is important to discuss carbon capture technologies because they help improve the environment and increase the sustainability of this technology.

Finally, gasification studies have been performed for various specific scenarios which are of interest. Analysis of gasification process in different gasification technologies shows varying performance levels. An analysis of a two stage entrained flow gasifier is performed in Refs. [3], and an analysis for fluidized bed reactors in Refs. [7,13]. Different technologies yield different performances. The conditions that are used in the before mentioned work all used varying conditions for the process which made it hard to distinguish which technology would yield the highest efficiency for a hydrogen producing process.

The purpose of this paper is to investigate the parameters that effect the production of hydrogen in an Integrated Gasifier for Hydrogen Production (IGHP). This is the system presented in the paper Combined Power and Hydrogen Production from Coal part a- Analysis of IGHP by Perna [6]. This study focuses on the energy and exergetic efficiency of the system which has not been completed in the previous work. A parametric study is performed to determine the optimal operating conditions of the IGHP so that it can produce the maximum amount of hydrogen and perform at its peak efficiency. A computer simulation using the software program Engineering Equation Solver (EES) is used as a simulation tool to model the system processes and predict system performance. Equilibrium based models are used in conjunction with thermodynamic balance equations for each component of the system to simulate the systems performance. The EES code calculates for the composition