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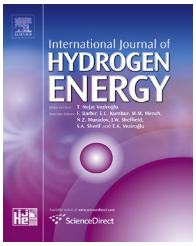

Production of synthesis gas from propane using thermal water vapor plasma

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ABSTRACT

In this work, an experimental plasma-chemical reactor equipped with a water vapor plasma torch was used for catalyst-free thermal plasma reforming of propane to produce a synthesis gas. Thermal arc discharge plasma (a mixture of water vapor and argon) was generated at atmospheric pressure.

The influences of the H_2O vapor and C_3H_8 flow rates on the syngas production, composition, and energy conversion efficiency as well as specific energy requirements were investigated. The best results were obtained under the experimental conditions of H_2O vapor flow rate of 360 l/min, C_3H_8 flow rate of 47 l/min, and input plasma torch power of 63 kW. The concentrations of the products were as follows: H_2 68.9%, CO 21%, CO_2 5%, CH_4 0.55%, and C_2H_2 0.9%. The C_3H_8 conversion ratio, H_2 yield, H_2 selectivity, and CO selectivity were 100%, 67%, 48.5%, 25.3%, respectively. The highest energy efficiency and the lowest specific energy requirement were 65% and 32.7 kJ/mol, respectively, and the H_2/CO ratio was 3.28. The modeling of chemical processes, based on the classical thermodynamic equilibrium reactor, was also proposed. The calculated data fit quite well the experimental results.

1. Introduction

In recent years, the interest to hydrogen and synthesis gas production has been increasing. Synthesis gas, a mixture of hydrogen and carbon monoxide, is a good intermediate for the production of pure hydrogen or other chemicals [1,2]. Hydrogen is characterized as a clean fuel and has the most appropriate characteristics for using it as a substitute in most energy systems. Moreover, the hydrogen energy offers good prospects for fuel cells and other energetic applications [3,4]. Therefore, syngas produced through fuel reforming could be an alternative partly reducing the dependence on traditional energy sources.

A set of developed conventional fuel-reforming methods such as dry reforming [5], autothermal reforming [6], steam reforming and partial oxidation [7,8], etc. have some technical and economic limitations, including the requirement of external high-temperature heat sources inducing the thermal absorption reaction, catalyst sensitivity to contaminants, requiring much equipment as well as high investment and exploitation costs.

As an alternative to the conventional means, the thermal plasma and non-thermal plasma reforming [9] methods have attracted attention as a way to overcome such limitations. The thermal plasma technology allows generating radicals and reactive species which can accelerate chemical reactions at low energy costs. In this case, plasma itself could be considered

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as a catalyst with the properties such as a high density of energy, high chemical reactivity, and high temperatures (several thousand Kelvin) as well as low investment costs and a better control of the process producing chemical non-equilibrium materials. However, the major disadvantage implying some restrictions of the thermal plasma process is relatively high electric energy consumption [10].

Lighter hydrocarbons such as methane, ethane or propane ensure a more stable operation process. Therefore, propane was chosen as a source material in steam reforming. Besides, propane is produced in relatively high amounts from natural gas and crude oil refining. For pressures above 9 bars, it is in a liquid state and can be easily stored and distributed [11,12]. Furthermore, propane is a major constituent of the inexpensive liquefied petroleum gas (LPG) [13,14].

In recent years, the interest to propane reforming by various plasma technologies (both thermal and non-thermal), such as thermal plasma [15–17], gliding arc discharge [18,19], corona discharge [20], spark discharge [21] and sliding discharge [22], has received significant attention. However, the chemistry mechanism of methane steam reforming using various plasma technologies is studied in more detail than propane plasma reforming. For this reason, there has been more reference works dedicated to this issue [23–26].

The present study deals with the propane steam reforming to synthesis gas using thermal arc discharge water vapor plasma at atmospheric pressure. The modeling of chemical processes, based on a classical thermodynamic equilibrium reactor (TER), was also proposed. First, thermodynamic equilibrium modeling was performed to determine the dominant species in water vapor plasma, which initiated chemical reactions. Later on, the effect of different parameters such as the variable water vapor flow rate and plasma torch power at a constant propane flow rate, and vise versa, on the reforming characteristics were studied. Additionally, quantification of the reforming system in the field of energy efficiency and specific energy requirement was performed, including a comparison with the other plasma methods. As a result, the thermal arc discharge plasma reformer directly involving water vapor as the plasma-forming gas could compete with other plasma means.

2. Experimental setup and methods

2.1. *Design of the thermal plasma reforming system*

The experimental system designed for this research is shown in Fig. 1. It consisted of an atmospheric pressure DC plasma torch, a power supply system, a chemical reactor, a gas supply system, a steam generator with a superheater, a condenser, and a gas chromatograph.

The ignited electric arc discharge between the cathode and anode of the linear DC plasma torch with the maximum capacity of 63 kW (voltage 0–340 V, current 0–200 A) was stabilized by a mixture of argon–water vapor. In order to protect the tungsten-rod cathode from erosion, argon was used with a flow rate of 17.4 l/min adjusted by a mass flow controller. Tangentially injected overheated water vapor was used as the main plasma-forming gas with the flow rates ranging within 213–360 l/min, adjusted by a needle-type mass flow controller. The flow rate of Ar was preserved in the range of 10–16% of the total mass flow rate. Propane was supplied from a cylinder at the flow rate within 21–47 l/min, adjusted by a mass flow controller.

The flow rates of the formed products were calculated from balance equations using the known flow rates of the reactants (Ar, H_2O, C_3H_8) and product concentrations measured with a gas chromatograph. Additionally, a flow meter was used after the condenser to measure the flow rate of gaseous products. Thus, it was easier to check whether the balance equations for all elements were valid after the flow rate calculation. The formation of carbon black could be calculated from the carbon

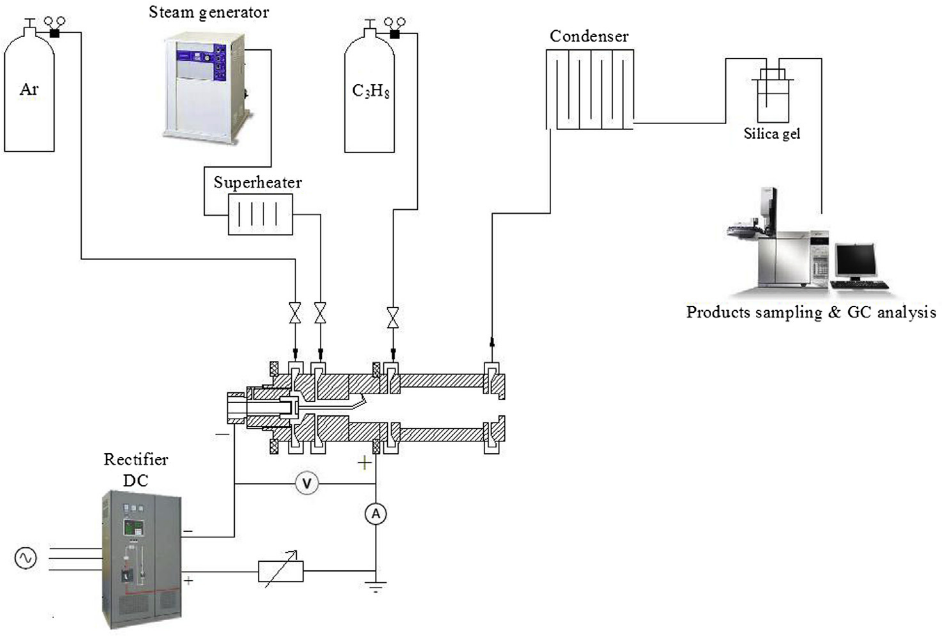

Fig. 1 – The schematic diagram of the thermal plasma reformer system.