

**Abstract**—Hydrogen is regarded to play an important role in future energy systems because it can be produced from abundant resources and its combustion only generates water. The disposal of waste tyres is a major problem in environmental management throughout the world. The use of waste materials as a source of hydrogen is particularly of interest in that it would also solve a waste treatment problem. There is much interest in the use of alternative feedstocks for the production of hydrogen since more than 95% of current production is from fossil fuels. The pyrolysis of waste tyres for the production of liquid fuels, activated carbons and gases has been extensively researched. However, combining pyrolysis with gasification is a novel process that can gasify the gaseous products from pyrolysis. In this paper, an experimental investigation into the production of hydrogen and other gases from the bench scale pyrolysis-gasification of tyres has been investigated. Experiments were carried using a two stage system consisting of pyrolysis of the waste tyres followed by catalytic steam gasification of the evolved gases and vapours in a second reactor. Experiments were conducted at a pyrolysis temperature of 500 °C using Ni/Al<sub>2</sub>O<sub>3</sub> as a catalyst. The results showed that there was a dramatic increase in gas yield and the potential H<sub>2</sub> production when the gasification temperature was increased from 600 to 900 °C. Overall, the process showed that high yields of hydrogen can be produced from waste tyres.

**Keywords**—Catalyst, Hydrogen, Pyrolysis, Gasification, Tyre, Waste

## I. INTRODUCTION

WASTE tyre disposal continues to be an economic and environmental problem. It is estimated that 3.4 million tonnes per year of waste tyres are generated in Europe [1], 4.6 million tonnes in the U.S. [2], greater than 1 million tonnes in Japan [3] and around 5 million tonnes in China [4]. There is a wide variation among regional and national governments in the methods in Europe used for dealing with this kind of waste. For example, the main methods for waste tyre management are materials recovery (38.7%), energy recovery (32.3%) and retreading (11.3%) [1]. In the U.S. however, the main methods for waste tyre management are tyre-derived fuel (52.8%), ground rubber (16.8%), and civil engineering applications (11.9%) [2].

One of the treatment options for waste tyre is incineration. The incineration process is exothermic [5] and the heat generated from incineration could be used as a source of steam for use directly for heating, air-conditioning and industrial processing or for use in steam turbine plants to produce electricity. However, incineration is not considered to be the most economical and environmental method [6].

With increasing interest in new technology, Pyrolysis could be considered as a new option for scrape tyre treatment. Pyrolysis is a thermal process that degrades the solid fuels in the absence of oxygen to generate different components which can be used in industrial applications.

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Pyrolysis of scrap tyres generates oil, char, gas and residual steel, each of which can be recycled, for example; the gas produced which has high calorific value can be used in the energy plant; the steel could be recycled in the steel industry; the oil can be used as supplementary fuel in furnaces and boilers and the char can be used as an activated carbon or black carbon [7]. The yield of tyre pyrolysis products is affected by different factors such as the operational conditions and reactor design. For example, it has been found that the gas yields varied between 2.4 and 14.8 wt.%, the liquid yields varied between 3.6 and 58.8 wt.% and the char varied between 94 and 26.4 wt.% when a static batch reactor was used and the pyrolysis temperature was varied between 300 and 720 °C [8]. The main products in the pyrolysis gases derived from tyre are hydrogen, methane, ethane, ethylene, propylene, butadiene and other hydrocarbons from C<sub>4</sub>-C<sub>6</sub> [7]-[9]. In addition, the pyrolysis oils products from tyre are very complex containing a wide variety of alkanes, alkenes and aromatic compounds [7]-[9].

Hydrogen can play a major role in future energy systems, since it is regarded as a clean energy source. About 5×10<sup>11</sup> Nm<sup>3</sup> of hydrogen is produced each year and about 96% of this amount is produced from fossil fuel. Hydrogen might be used as a fuel in internal combustion engine and can be used in fuel cells [10].

In this paper, the potential to produce high yields of hydrogen from waste tyres has been investigated during a steam catalytic pyrolysis-gasification process. This process was carried out in a two-stage fixed bed reaction system, with a Ni/Al<sub>2</sub>O<sub>3</sub> catalyst when the gasification temperature was increased from 600 to 900 °C.

## II. EXPERIMENTAL

The waste tyres used in this study were from passenger cars and consisted of the rubber tread with steel removed and was shredded to a particle size of about 6 mm. The Ni/Al<sub>2</sub>O<sub>3</sub> catalyst was prepared by an incipient wetness method using Al<sub>2</sub>O<sub>3</sub> and an aqueous solution of Ni(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O. After loading the nickel onto the Al<sub>2</sub>O<sub>3</sub> (10 wt.% Ni), the catalyst was dried at 105 °C overnight, and calcined at 500 °C for 3h under an air atmosphere. The catalyst was sieved to granules with a size less than 0.212 mm.

Scanning electron microscopy (SEM) (Phillips XL30 Environmental) was used to investigate the surface morphology of the carbon deposited on the used catalysts.

Waste tyre catalytic pyrolysis-gasification was conducted using a two stage fixed bed reactor. A schematic diagram of the experimental system is shown in Figure 1. Experiments were conducted at a pyrolysis temperature of 500 °C and gasification temperature was varied from 600 to 900 °C. Approximately 1.0 g of waste tyre was held in the first pyrolysis reactor and 0.5 g catalyst, supported on quartz wool, was held in the second gasification reactor. Water was introduced by a syringe pump into the second gasification reactor and before the catalyst.

The products from the second stage passed through an air-cooled condenser and two dry ice cooled condensers where the liquid products were collected.

The non-condensable gases were collected with a 25 L Tedlar gas sample bag and were analysed off-line using packed column gas chromatography (GC). Hydrocarbons from C1 to C4 were detected using a Varian 3380 gas chromatograph with a flame ionization detector (GC/FID). Permanent gases were detected using two separate packed columns with a second Varian 3380 gas chromatograph with two thermal conductivity detectors (GC/TCD).

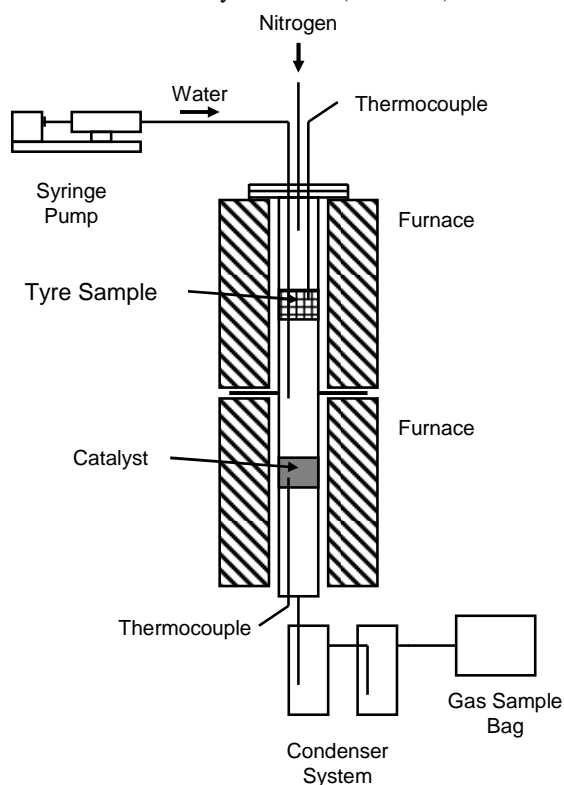


Fig. 1 Schematic diagram of the two-stage pyrolysis gasification experimental system

### III. RESULTS AND DISCUSSION

Table I shows the product yield from the catalytic steam pyrolysis-gasification of waste tyres at different gasification temperatures. It is shown that the gas yield largely increased from 14.3 wt.% to 56.8 wt.% and the oil yield significantly decreased from 38.6 wt.% to 19.5 wt.% when the gasification temperature was increased from 600 to 900 °C. The high overall yield above 100 wt.% also includes the reacted water from the steam and also the formation of CO and CO<sub>2</sub> from the steam. The product yield trend with increasing temperature was similar to those reported from literature [11], [12]

GASIFICATION TEMPERATURE (°C)	600	700	800	900
GAS/TYRE (WT.%)	14.3	30.6	39.8	56.8
SOLID/TYRE (WT.%)	43.3	44.5	41.7	39.6
OIL/TYRE (WT.%)	38.6	33.1	31.9	19.5
MASS BALANCE (WT.%)	96.2	108.2	113.5	116.0

Fig. 2 shows the gas composition from the catalytic steam pyrolysis-gasification of waste tyres at different gasification temperatures. The H<sub>2</sub> concentration decreased when the gasification temperature was increased from 600 to 800 °C, and then increased with an increase in gasification temperature to 900 °C. The CO concentration increased and the hydrocarbon gases decreased, when the gasification temperature increased.

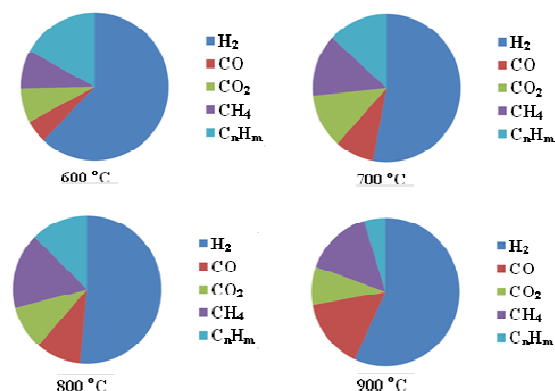


Fig. 2 Gas composition at the different gasification temperature

Fig. 3 shows the potential hydrogen production from the catalytic steam pyrolysis-gasification of waste tyres at different gasification temperatures. In this work the potential hydrogen production is defined as the percentage of the hydrogen produced from the pyrolysis-gasification process in relation to the maximum theoretical amount of H<sub>2</sub> available in the tyre rubber. The potential H<sub>2</sub> production was largely increased from 3.2 to 13.1 wt.% when the gasification temperature was increased from 600 to 900 °C.

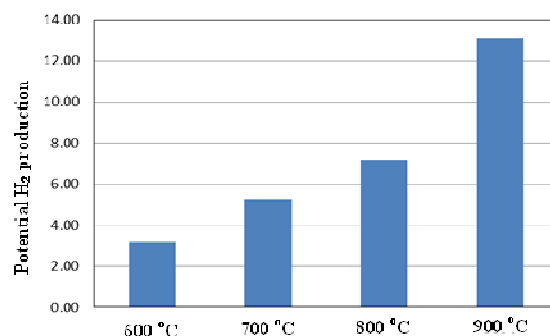


Fig. 3 Potential hydrogen production at the different gasification temperature

The Ni/Al<sub>2</sub>O<sub>3</sub> catalyst after reaction in the pyrolysis steam catalytic gasification of waste tyre was analysed by SEM to investigate the surface characteristics. Fig. 4 shows the SEM analysis of the reacted Ni/Al<sub>2</sub>O<sub>3</sub> catalyst at a gasification temperature of 800 °C. The results showed that the reacted Ni/Al<sub>2</sub>O<sub>3</sub> was deposited with large amounts of filamentous carbons, and the total amount of coke deposited on the catalyst was 18.2 wt%. Filamentous carbons on reacted catalyst have been extensively reported and observed using SEM. For example, a Ni/Al<sub>2</sub>O<sub>3</sub> catalyst was used to produce hydrogen from the pyrolysis, steam catalytic gasification of polypropylene for a gasification temperature of 800 °C and

showed the formation of filamentous carbon on the reacted catalyst surface using SEM [13]

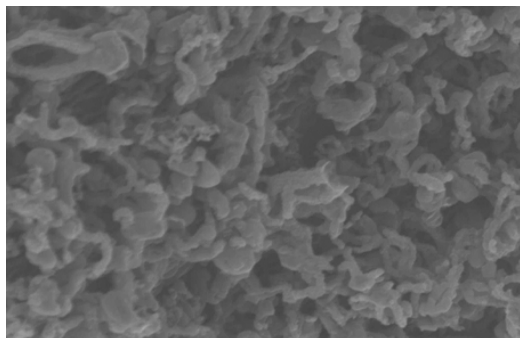


Fig. 4 Scanning electron micrograph of the reacted catalyst

#### IV. CONCLUSIONS

This study aims to provide information on the feasibility to produce hydrogen by catalytic steam gasification of waste tyres in a two-stage reactor. In order to achieve the desired result, a hydrogen production from waste tyre was investigated using a two-stage pyrolysis-gasification reactor and Ni/Al<sub>2</sub>O<sub>3</sub> as a catalyst. The results show that the gas yield and the potential hydrogen production largely increased when the gasification temperature was increased from 600 to 900 °C. The carbon deposited on the used catalyst was characterized by Scanning electron microscopy. The result shown that the reacted catalyst contained coke deposits on the surface of the catalyst with large amount of filamentous carbons and a total coke deposition was 18.2 wt%.

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