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Steam reforming of biomass gasification gas for hydrogen production: From thermodynamic analysis to experimental validation

João Brito [a,b], F. Pinto [c], Alexandre Ferreira [b,d], M.A. Soria [a,b,*], Luís M. Madeira [a,b]

[a] LEPABE – Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

[b] ALiCE - Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

[c] LNEG, Laboratório Nacional de Energia e Geologia, Unidade de Bioenergia e Biorrefinarias, Estrada do Paço do Lumiar, Lisboa 1649-038, Portugal

[d] LSRE-LCM - Laboratory of Separation and Reaction Engineering – Laboratory of Catalysis and Materials, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, Porto 4200-465, Portugal

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ABSTRACT

Biomass gasification produces syngas composed mainly of hydrogen, carbon monoxide, carbon dioxide, methane, water, and higher hydrocarbons, till C_4, mainly ethane. The hydrocarbon content can be upgraded into richer hydrogen streams through the steam reforming reaction. This study assessed the steam reforming process at the thermodynamic equilibrium of five streams, with different compositions, from the gasification of three different biomass sources (Lignin, Miscanthus, and Eucalyptus). The simulations were performed on Aspen Plus V12 software using the Gibbs energy minimization method. The influence of the operating conditions on the hydrogen yield was assessed: temperature in the range of 200 to 1100 °C, pressures of 1 to 20 bar, and steam-to-carbon (S/C) molar ratios from 0 (only dry reforming) to 10. It was observed that operating conditions of 725 to 850 °C, 1 bar, and an S/C ratio of 3 enhanced the streams' hydrogen content and led to nearly complete hydrocarbon conversion (>99%). Regarding hydrogen purity, the stream obtained from the gasification of Lignin and followed by a conditioning phase (stream 5) has the highest hydrogen purity, 52.7%, and an hydrogen yield of 48.7%. In contrast, the stream obtained from the gasification of Lignin without any conditioning (stream 1) led to the greatest increase in hydrogen purity, from 19% to 51.2% and a hydrogen yield of 61.8%. Concerning coke formation, it can be mitigated for S/C molar ratios and temperatures >2 and 700 °C, respectively. Experimental tests with stream 1 were carried out, which show a similar trend to the simulation results, particularly at high temperatures (700–800 °C).

1. Introduction

We live in a growing and highly technological society that claims vast amounts of energy. Unfortunately, >80% of the world's energy demand is fulfilled via non-renewable energy sources and fossil-based fuels [1], intensifying the global warming problem due to the release of greenhouse gases. Also, the dependence on fossil fuels creates serious worries over oil and natural gas exhaustion in a relatively short period [2]. So, more sustainable solutions must be found to achieve the maximum 1.5 °C temperature increase relative to the pre-industrial levels, as settled in the Paris agreement [3]. Renewable energies are expected to play a key role in reducing carbon dioxide emissions [4].

Hydrogen is the prime candidate for the energy transition due to its high energy content per mass unit, 2.5 and 3 times higher than methane and gasoline, respectively, and its final use does not release greenhouse gases [5]. However, despite being the most abundant element in the universe, it cannot be found in its pure state, and 96% of hydrogen is produced from fossil fuels, i.e., natural gas and coal. Natural gas is commonly used for the methane steam reforming technology that is responsible for 75% of the produced hydrogen [6]. The dependence on gas and coal produces considerable amounts of carbon dioxide, being released 10 or 19 tonnes of carbon dioxide per tonne of hydrogen produced when using natural gas or coal, respectively [7].

Hydrogen production based on biomass is considered a viable alternative, as it is widely available, inexpensive, and carbon neutral [8,9]. The biomass resource is available in forests, agricultural residues, and organic wastes from human and animal activities [10,11]. Various

* Corresponding author at: LEPABE – Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal.

E-mail address: masoria@fe.up.pt (M.A. Soria).

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