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Effect of inert metal foam matrices on hydrogen production intensification of methane steam reforming process in wall-coated reformer

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ABSTRACT

Numerical modeling of a heated mixture of methane with steam in 2D plane Wall-Coated Steam Methane Reformer (WC-SMR) with surface catalytic reaction at industrial conditions has been performed. The modeling was performed within the framework of Navier-Stokes equations for a laminar flow of a multi-component compressible gas. The influence of the insertion of non-catalytic nickel-based metal foam matrices in the catalytic zone of the WC-SMR on the hydrodynamic, thermal and mass behaviors of the gas mixture and its distribution along the reactor have been investigated. Three different Metal Foam (MF) samples have been investigated and then compared: Ni-Foam, Ni-Cr-Foam and Ni-Fe-Cr-Foam. It has been shown that not only the use of metal foam matrices but also their thermo-physical properties are important to improving the WC-SMR efficiency. It is demonstrated that such material can bring a significant enhancement for hydrogen production, heat and mass transfer processes. 16.91% of improvement in terms of H_2 production is realized.

Introduction

The fossil energy sources have powered the world economy since the beginning of the industrial revolution in the 18th century. Their usage has been increasing in line with the growth of the economic need. Over the past 20 years, nearly three-fourths of human-caused emissions came from the burning of fossil fuels which causes enormous strains to the environment [1]. The global energy consumption based on the conversion of fossil fuels is worrying today, and the use of alternative energy resources are emerging as promising solution to limit the impact of the environmental issues. Progress is being made on the sustainable energy supply system to hybridize or replace the conventional energy systems. Electricity and hydrogen are considered as the future energy carriers. The hydrogen mays be used as a fuel and electricity source. At present, hydrogen is produced almost entirely from fossil fuels such as natural gas, naphtha, and coal [2], via numerous processes which are most economical or consciously preferred [3], such as Steam Reforming of Methane (MSR), or catalytic partial oxidation (POX) of hydrocarbon fuels.

Nowadays, over 90% of the world's total hydrogen production is derived from methane, a primary component of natural gas, via the MSR process [4], [5]. Most of the remaining

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hydrogen production is accomplished via coal gasification and water electrolysis (at a smaller scale) [6]. In the foreseeable future, the natural gas will continue to be the major feedstock for hydrogen production [7].

The high frequency of studies appearing in the literature attests to the importance of the MSR process optimization by developing new reactors and improving their performance [8]. To do so, Innumerable intensification processes have been used: reactor configuration studies [9–14]; catalyst development [15–18]; structured catalyst support [19–21].

On the one hand, the optimization of the reactor configuration is a proven way to maximize the efficiency of MSR systems. Yun et al. [22], investigated by experimental approach the main parameters of MSR reaction in shell-and-tube Steam Methane Reformer (SMR) to improve hydrogen production. To do so, the authors compared four configurations of SM-Ref. The analysis shows that the hydrogen production is mainly affected by the heat supply of the endothermic reaction. To enhance the heat supply while minimizing the heat loss, the authors proposed the installation of void space before the reforming region. In addition, the flow into the reformer tubes is improved by using baffles at the outlet of reformer. In Ref. [9], Zanfir and Gavriilidis explored numerically MSR reaction coupled with methane catalytic combustion in a co-current catalytic plate reactor. Their 2D symmetric model showed that, at constant velocity, the axial temperature gradient increased with respect to the channel height varied from 1 mm to 4 mm. They affirmed that larger dimensions of channels caused less efficient heat transfer and thus a low methane conversion. In addition, the increasing of the catalyst thickness led to decrease the outlet conversions by 30% for both studied reactions.

Similarly, Chen et al. [23] studied numerically a coupled MSR reaction with catalytic combustion to explore the design para meters on H_2 production yield, such as the channel height, the inlet S/C ratio, the wall thermal conductivity and the catalyst type. The authors demonstrated that optimal designing which considers the main parameters could lead to stable microreactor functioning and thus more efficient performance. In the same perspective, Dokamaingam et al. [10] conducted a numerical study on a Solid Oxide Fuel Cell (SOFC) system coupling endothermic reforming process with exothermic electrochemical reactions. Their analysis aimed to address reformer entrance issues for the conventional backed-bed reformers, namely the quick consumption of methane and the presence of undesirable local cooling. The results showed that the use of Wall Coated Steam Methane Reformer (WC-SMR) allows smoother methane consumption and an efficient thermal behavior limiting thus local cold spots at the entrance of the reformer. Moreover, a recent study conducted by Shin et al. [13] on the engine-hybrid stationary fuel cell systems demonstrates the importance of the heat management to achieve optimal methane conversion rates. In their work, low-temperature non-reactive heat source is imposed to ease thermal energy transfer to the reaction zone of the steam reformer. The findings showed that the heat transfer dominates strongly the methane conversion rate, what makes the temperature uniformity crucial for improving the produced hydrogen amount. Wu et al. [24], studied numerically a predictive control model of MSR reaction process in one of the 336 reforming tubes in an industrial-scale co-current reformer [25]. In the basis of the wall temperature at the reforming tube outlet, the proposed model aimed to regulate the H_2 outlet concentration where the reforming channel is confronted to tube-side feed disturbances. The designed feedback control is compared to classical controller. The authors demonstrated the value of the implementation of such performant controller which leads to minimize the settling time comparing to classical controllers. To optimize the thermal efficiency of steam reformers, Tran et al. [26], conducted a CFD study integrated with data-based optimization procedure. The developed furnace-balancing scheme aims to determine optimal feed distribution at the furnace-side by evaluating the reformer performances. The authors affirm that such procedure could reduce the nonuniformity of temperature surrounding the reforming tube outlet leading to optimal operation of the industrial-scale reformer.

On the other hand, the development of new catalysts has been the subject of numerous studies in the literature, more particularly the use of non-precious metal alloy catalysts for the MSR process. The optimization of the catalyst deposition was specifically investigated to improve the reformer efficiency and reduce the economic cost and environmental impacts of such process. For such a purpose, Wang et al. [27] conducted experimental and numerical study to analyze the MSR kinetic in micro-channel reactor coated with NiO/Al_2O_3 catalyst. The heat supply and catalyst activity of the MSR process were discussed. They conclude that optimal reactor performance can be reached by coupling thermally the reactor to exothermic reaction, and by optimizing the catalyst activity. Dong et al. [28] investigated the influence of adding nickel (Ni) to Ce-ZrO_2 support. The variation of the Ni proportion in the Ce-ZrO_2 support has led the authors to determine the critical ratio providing the highest catalytic activity and remarkable stability. The methane conversion increases with increasing Ni ratio up to 15 wt. %, while it decreases exceeding this value.

Structuring supports have also been discussed intensively for MSR applications. Impregnation of catalyst in structured support fosters the reactive gas/catalyst interaction and leads to optimize the mass and heat behaviors during the reactive process and in turn leading to improve the methane conversion. In light of this, Ricca et al. [15] proposed new catalyst design to enhance the MSR reaction. The experiment tests carried out on the use of structured catalyst as Silicon Carbide (SiC) monolith, presenting high thermal and mechanical properties, would increase the heat transfer along the catalyst bed and lead to maximize the overall conversion rate. Palma et al. [29], compared different structured catalysts in terms of thermal distribution. The Ni-based structured catalysts were prepared experimentally and compared with commercial one to analyze the catalyst activity. The results show that structured catalyst leads to maximize heat and mass transfer phenomena. In addition, high catalyst activity is reached, thus allowing a strong intensification of MSR reaction process. The quantity of catalyst impregnated in the structured reactors is not proportional with the hydrogen production rate. Lee et al. [30] investigated numerically and experimentally a configuration of packed catalysts for hydrogen production, their approaches led to propose a new configuration for the backed