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A compact catalytic foam reactor for decomposition of ammonia by the Joule-heating mechanism

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ABSTRACT

Ammonia (NH_3) is a viable hydrogen (H_2) carrier that allows storage and transport of H_2 using well-established infrastructure while maintaining high H_2 storage density. However, cracking NH_3 into H_2 is energy-intensive. Herein, direct Joule-heating of the NiCrAl foam catalyst support is suggested and demonstrated, to minimize heat transfer scale for lower reactor volume, higher efficiency and power density than previously reported reformers. The power density of 128 $W/cm^3_{Reactor}$ is achieved based on the lower heating value of H_2: this is 90% higher than previously reported microreactors. Also, even in a small-scale demonstration with a low internal volume of 7.7 cm^3 and a high surface-area-to-volume ratio of 5.7 cm^{-1}, a high reforming efficiency of 69.2% is achieved with low catalyst loadings, showing the feasibility of the concept. The as-proposed reactor concept offers a strong prospect for facile adoption of the power-to-X scheme for numerous applications including H_2-fueled islanded networks, and decarbonized energy conversion.

1. Introduction

As the detrimental effects of using hydrocarbon fuels are becoming rapidly tangible in daily life, campaigns for reducing the use of fossil fuels and replacing them with clean energy sources are surging. Hydrogen (H_2) is one of the promising alternatives as a chemical energy carrier. However, despite its high gravimetric energy density, *i.e.,* high heating value (HHV) of 141.91 MJ/kg [1], its low volumetric energy density, *i.e.*, 0.01 MJ/L at 0 °C and 1 atm [2], poses a challenge for H_2 to fully reach its potential as a prominent energy carrier. H_2 can be safely stored and transported via the available chemical H_2 carriers such as ammonia (NH_3), methanol [3], liquid organic hydrogen carriers (LOHCs) [4], formic acid [5], and formate [6]. Among these, NH_3 has the highest gravimetric and volumetric hydrogen storage density (ca. 17.8 wt%, 108 g/L at 20 °C and 8.6 bar [7]) while offering zero carbon emissions during dehydrogenation (*i.e.*, H_2 release by chemical reaction) and no side reactions. Annually, NH_3 is produced by millions of tons (estimated 150 Mt in 2019 [8]) and transported for numerous industries including agriculture, chemicals, and pharmaceuticals. Hence, the infrastructure hitherto exists, and portable use of NH_3 as an H_2 carrier is feasible. Conversion of NH_3 to H_2, however, is highly endothermic, and providing an efficient heat source for this reaction requires advances in both the material and reactor designs. Therefore, studies have been conducted to address these challenges. For example, with advances in catalyst design, a decomposition temperature of 500 °C for > 99.9% NH_3 conversion has been reported [9]. Nevertheless, the application of sustainable heat sources and delivering the required thermal energy even at this temperature is still a restricting challenge for the use of NH_3 as a reliable H_2 carrier. Therefore, devising a mechanism under the power-to-X scheme [10], in which surplus electric power can be used for other types of energy storage and conversion, should be of main concern for the development of viable NH_3-driven energy industry.

Some methods have been proposed and investigated for efficient delivery of heat via the autothermal design of reactors. Autothermal design refers to the thermally-coupled decomposition-oxidation reactors. Related reports are mostly inclined towards thermal coupling of NH_3 decomposition reactor with oxidation reactors fueled with NH_3 [11–13] and/or hydrocarbons [14,15]. However, heat loss resulted from these designs is a major issue. In some reports, process intensification

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