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Hydrogen and syngas production by superadiabatic combustion – A review

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HIGHLIGHTS

- A review on application of superadiabatic combustion for H_2 and syngas production.
- Conversions of hydrocarbon fuels including biomass and hydrogen sulfide are focused.
- It covers non-catalytic TPOX, HFC, hybrid PM-catalyst reactor and SAC without PM.
- Separate sections deal the numerical modeling trends and the R&D challenges ahead.
- There is wide scope for further research on SAC reactors with and without PM.

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ABSTRACT

The application of superadiabatic combustion (SAC) technology for hydrogen and syngas production has been a focus of intensive research in the recent past. A lot of researches have been reported on the conversion of various gaseous and liquid hydrocarbon fuels, hydrogen sulfide and biomass into hydrogen or syngas, by using SAC. The porous medium combustion has been recognized as the most feasible technique to realize SAC, and few recent studies reported to have achieved SAC even without a porous medium (PM). This article compiles the works done so far in this area and suggests future directions. Following the general background, the history of hydrogen/syngas production by SAC is provided. Further developments are organized in the subsequent sections, which include all the published works on SAC-based hydrogen production from hydrocarbon fuels, hydrogen sulfide and biomass. The works on hybrid PM-catalyst filtration combustion and numerical modeling of SAC-based hydrogen/syngas production are discussed in separate sections. Subsequently, the development of SAC reactor without PM is presented, followed by summary and conclusion. This review reveals that there is a wide scope for future research particularly on hybrid-filtration combustion, biomass gasification, hybrid PM-Catalyst reactors, SAC reactors without PM, and on development of efficient reformers for practical stationary and portable applications. Scope is also open for detailed characterizations, both experimental and numerical, with various PM materials and structures and with variety of fuels under realistic operating conditions.

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Nomenclature

Abbreviations

ATR	autothermal reforming
CFD	computational fluid dynamics
DATR	dry autothermal reforming
FC	filtration combustion
GTI	Gas Turbine Institute
HFC	hybrid filtration combustion
HFO	heavy fuel oil
IPM	inert porous medium/media
LHV	lower heating value
LCA	life cycle assessment
LCC	life cycle costing
PM	porous medium/media
PMC	porous medium/media combustion
POX	partial oxidation
R&D	research and development
RFB	reciprocating flow burner
SAC	superadiabatic combustion
SR	steam reforming
SCT-CPO	short contact type catalytic partial oxidation
TPOX	thermal partial oxidation
UFL	upper flammability limit
UIC	university of Illinois at Chicago
YZA	Yttrium stabilized zirconia

Symbols

Al_2O_3	alumina
CO	carbon monoxide
CO_2	carbon dioxide
g	specific flow rate of fuel-air mixture
H_2	hydrogen
H_2S	hydrogen sulfide
J	Joule
kg	Kilogram
MJ	Mega Joules
MPa	Mega Pascal
SiC	silicon carbide
SiSiC	siliconized silicon carbide
T_{ap}	air preheating temperature
T_{max}	maximum combustion temperature
t_r	residence time
v_m	mixture velocity
v_{wp}	wave propagation velocity
v_f	filtration velocity
ZrO_2	zirconia
χ	water fraction
φ	equivalence ratio
η_c	conversion efficiency/hydrogen or syngas yield

1. Introduction

Hydrogen (H_2) is the simplest element on the earth and it has the highest energy content per unit mass (141.9 MJ/kg) of any other fuel, and has essentially no emissions when electro- chemically converted to electricity in a fuel cell [1]. These are few of the unique features that make H_2 the fuel for the future. Hydrogen-based power systems, such as fuel cells, are promising clean energy technologies; however, a significant obstacle is the production and distribution of H_2 [2]. Hydrogen is primarily bound into other molecules such as hydrocarbons, and the conversion of a hydrocarbon into hydrogen or synthesis gas (syngas- a mixture of CO and H_2) is accomplished through either catalytic or non-catalytic processes [3]. Hydrogen can be produced from fossil fuels by thermochemical processes such as steam-reforming (SR), auto-thermal reforming (ATR) and thermal partial oxidation (TPOX), from water by electrolysis (electricity source can be renewable energy or nuclear energy), from biomass by thermochemical and biological processes, and from ammonia and hydrogen sulfide (H_2S) [4]. Almost 98% of the annual production of hydrogen (mainly used in oil refineries, and for ammonia and methanol production) is from the reforming of fossil fuels [5]. An exhaustive review of the H_2 production technologies, and H_2 storage and purification methods was provided by Holladay et al. [6], while Abbas and Daud [5] reviewed the H_2 production techniques by methane decomposition. A recent review by Hassan and Khandelwal [7] has outlined the key H_2 reforming technologies with specific focus on aircraft engine application. If the hydrogen source is a hydrocarbon fuel, the immediate product of SR, TPOX and gasification would be syngas. However, in the ATR process, the hydrogen is separated from syngas by water-shift reaction, releasing carbon dioxide (CO_2) as the waste product. Syngas has attraction as a fuel for internal combustion engines, gas turbines and high temperature fuel cells, and as a chemical feedstock for the production of ammonia, methanol, higher alcohols, detergents and synthetic hydrocarbon fuels [6,8,9]. Therefore, researchers give individual importance to syngas while dealing with H_2 production from hydrocarbon sources.

Partial oxidation and auto-thermal reforming processes usually involve a catalyst that enhances conversion, but a catalyst is prone to poisoning and requires great care with the sulfur content of the fuel and with particulates; the catalysts involved are also expensive and prone to damage [2,10]. Furthermore, for most fuels, operating above the upper flammability limit (UFL) is essential to maximize the H_2 production; extending the flammability range can be achieved by recirculation of heat and product, use of catalysts or injection of radicals from plasma jets [11]. Thus, the absence of a catalyst necessitates a high reaction temperature [12], which calls for reforming processes that ensure operation above UFL with reactor cores possessing adequate thermophysical characteristics (particularly un-damageable). The superadiabatic combustion (SAC), wherein the combustion takes place above the adiabatic temperature of the reactant mixture, has been well identified as a viable option to realize reactors operating above UFL [13–15]. It is also well known that combustion inside a porous medium (PM) is the widely adopted mechanism to realize SAC by facilitating internal heat recirculation, and hence is one of the most promising non-catalytic thermal partial oxidation (TPOX) techniques for the production of H_2 and syngas [1]. The PM could be a fluidized or a stationary bed. In a fluidized bed system, the