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Experimental and analytical study of a porous media reformer with passive air entrainment

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ABSTRACT

A porous media fuel reformer featuring passive air entrainment and a surface-stabilized flame is demonstrated and utilized for the reformation of methane. Passive air entrainment negates the need for auxiliary resources beyond a source of compressed fuel gas for operation, making a reformer of this design promising for applications such as replacement of hydrocarbon flaring with syngas generation at isolated oil and gas production sites and generation of syngas in other remote locations. The porous media reformer design presented in this study incorporates an eductor to entrain ambient air and a swirl mixing chamber and porous media bed to premix fuel and oxidizer before combustion. A range of methane flow rates was tested in this study, and the effect on air entrainment, and therefore equivalence ratio, was examined. A wide range of stable operating conditions shows a large turndown ratio of the reformer and burning rate ratios greater than unity. Fuel conversion efficiency and syngas production were evaluated and concentrations of methane, hydrogen, carbon monoxide and carbon dioxide are presented for a range of methane flow rates. Product compositions are compared to equilibrium and a high extent of fuel conversion efficiency is shown. An analytical model that accounts for reformer geometry and operating conditions to predict air entrainment and equivalence ratio is presented and compared with the experimental results. The analytical model compares favorably with the experimental results and can guide future reformer development and scaling.

Introduction

Extensive research has examined catalytic and non-catalytic routes for reforming fuels to hydrogen-rich synthesis gas, or syngas. Thermal partial oxidation for syngas production has been shown to be a robust technique that is tolerant to wide variations in fuel composition [1–6], and heat recirculation is frequently used to extend flammability limits and accelerate conversion rates [7–12]. While highly effective in reforming fuels to hydrogen-rich syngas, filtration combustors and other heat-recirculating reactors often need to be actively controlled to overcome operational challenges such as propagating flame fronts, flashback, and soot formation [5,13–15]. There are scenarios in which fuel reformation could be implemented but the costs and complexities associated with catalytic or excess enthalpy techniques are currently prohibitive. Oil and gas production, for example, produce significant amounts of fuel waste that could be converted to syngas, and the likelihood of industries doing so is significantly improved if a

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Nomenclature

A	cross-sectional area, [m^2]
BRR	burning rate ratio
d_p	bead diameter, [m]
k_{eff}	effective loss coefficient
L	length of the bed, [m]
$\dot{n}$	molar flow rate
P	pressure, [Pa]
Pe	peclet number
Q	flow rate at room temperature, [m^3/s]
S_L	flame speed, [m/s]
T	temperature, [K]
U	superficial velocity at the cross section of the bed, [m/s]
V	velocity, [m/s]

Greek symbols

ϕ	equivalence ratio
α	thermal diffusivity, [m^2/s]
μ	dynamic viscosity, [Ns/m^2]
∞	atmospheric condition
ε	porosity
η	conversion efficiency of methane, [%]
ρ	density, [kg/m^3]

Subscript

a	air at ambient temperature
FS	flame speed
g	methane at ambient temperature
h	exit of the burner
i	fuel injector orifice in eductor
l	inlet of the burner
m	air-fuel mixture
m,m	mixture at average porous media bed temperature
p	porous media bed
t	eductor throat

robust and low cost method is available. Significant quantities of natural gas and larger hydrocarbons are currently flared at oil production sites that do not have sufficient auxiliary resources, such as electricity, to provide active control of flare gas combustion. Associated gas is sometimes used at these sites to provide pneumatic motive force for early oil production and equipment, after which the gas is flared. Additionally, natural gas wells that are drilled but not used for production will have a period of flaring prior to being temporarily shut [16]. Since hydrocarbons have at least ten times higher global warming potential by weight than carbon dioxide [17], and direct release of large amounts of combustible gas can produce an explosion hazard near the production site, unused gas is flared instead of released directly into the atmosphere. Flaring of hydrocarbon-rich gases has increased significantly in the past decade due to advanced oil recovery efforts in formations that produce natural gas in addition to oil [18], and flaring has contributed significantly to an increase in greenhouse gas emissions. Incomplete combustion of flare gas can produce significant amounts of pollutants that damage the environment and human health, leading to cancer and neurological, reproductive and developmental effects [19]. One of these pollutants is soot, which is hazardous to inhale due to small particle sizes that can travel readily into lungs and is known to contribute to climate change through high absorption of solar radiation, called radiative forcing [20,21].

This study focuses on development and use of a porous media reformer to convert hydrocarbon fuels, which are currently flared or otherwise wasted, to clean burning and utilizable synthesis gas. Such synthesis gas could be upgraded, utilizing only the hydrogen content or the hydrogen and carbon monoxide, or burned directly for power production. The reactor presented in this study incorporates design features to promote air entrainment and premixing in order to produce combustible reactants for maximal combustion efficiency. One of these design features is an eductor, which utilizes the momentum of a pressurized fuel gas jet to entrain ambient air into the fuel gas stream. Another feature is a swirl chamber, which mixes the fuel and gas by inducing swirl in the flow as it enters the burner body [22]. A third significant feature is the porous media bed; porous media has been widely used in the construction of experimental combustion devices to promote premixing and preheating of reactants prior to combustion [23–25]. Heat transfer through porous media has been extensively studied, and found to improve with decreasing media porosity [26]. In addition to heat recirculation, porous media also promotes premixing of gases through its pore networks [27]. The burner design presented in this study utilizes porous media to premix fuel and air and recirculate heat from the flame in order to preheat incoming reactants and promote flame stability over a wide range of fuel flow rates and equivalence ratios. Porous media has also been observed to slightly dampen burner acoustics during operation, which could assist in mitigating noise from industrial flares [28].

The present study experimentally and analytically examines operation of the porous media reformer with a surface-stabilized flame because the surface flame permits safe operation without risk of flashback over a wide range of operating conditions, and the surface flame reduces the risk of carbon build-up within the porous media bed from pyrolysis of large hydrocarbons at elevated temperatures [5]. This mode of operation is achieved by the use of fine diameter porous media and a range of high fuel flow rates over which the reformer is operated. A surface-stabilized flame distinguishes the current approach from many other burner methods and designs which utilize a submerged flame, and is intended to permit operation over long periods of time without the need for active control or additional methods of flame stabilization [29]. Equivalence ratios and syngas production are quantified by experimental measurements. An analytical model of the reformer is presented that predicts the rate of air entrainment into the fuel stream, and therefore reactant equivalence ratio, as a function of geometric and operating parameters. The model also provides guidelines for geometric scaling, permitting the future construction of a reformer that is capable of accommodating a wide range of reactant flow rates for a given application.