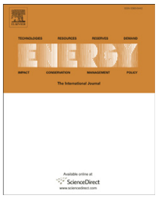
ARTICLE IN PRESS

Energy xxx (2014) 1–12

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Power and hydrogen production from ammonia in a micro-thermophotovoltaic device integrated with a micro-reformer

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ARTICLE INFO

Article history:
Received 4 October 2013
Received in revised form
26 May 2014
Accepted 13 June 2014
Available online xxx

Keywords:
Thermophotovoltaic
Ammonia
Hydrogen
Micro-emitter
Micro-reformer

ABSTRACT

Power and hydrogen (H_2) production by burning and reforming ammonia (NH_3) in a micro-TPV (microscale-thermophotovoltaic) device integrated with a micro-reformer is studied experimentally. A heat-recirculating micro-emitter with the cyclone and helical adapters that enhance the residence time of fed fuel-air mixtures and uniform burning burns H_2-added NH_3-air mixtures. A micro-reformer that converts NH_3 to H_2 using ruthenium as a catalyst surrounds the micro-emitter as a heat source. The micro-reformer is surrounded by a chamber, the inner and outer walls of which have installations of gallium antimonide photovoltaic cells and cooling fins. For the micro-reformer-integrated micro-TPV device the maximum overall efficiency of 8.1% with electrical power of 4.5 W and the maximum NH_3 conversion rate of 96.0% with the H_2 production rate of 22.6 W (based on lower heating value) are obtained, indicating that the overall efficiency is remarkably enhanced compared with 2.0% when the micro-TPV device operates alone. This supports the potential of improving the overall efficiency of a micro-TPV device through integrating it with a micro-reformer. Also, the feasibility of using NH_3 as a carbon-free fuel for both burning and reforming in practical micro power and H_2 generation devices has been demonstrated.

1. Introduction

Recent advances in portable electronic devices demand light, fast charging and long-durable portable power sources. Satisfying the demands due to their high mass-based energy density, combustion-driven miniature or micro-TPV (micro-scale thermophotovoltaic) devices have been considered as one possible alternative to replace current lithium-ion batteries since they are easily scaled down due to their simple structure without moving parts [1]. Various configurations of micro-emitters (micro-combustors) have been suggested for the micro-TPV devices: simple cylindrical combustors with a backward facing step [2–4], liquid fuel-film combustors [5,6], percolated platinum emitters [7], gas-fired metal radiant combustors [8,9] and heat-recirculating combustors [10–12].

Recently, the potential of ammonia (NH_3)–hydrogen (H_2) blends as a carbon-free, green fuel in a 1–10 W micro-TPV device has been experimentally evaluated in this laboratory [13], while hydrocarbon fuel has been generally considered for previous studies on the micro-TPV devices [5,6,8–12]. In particular, the NH_3–H_2 blend-fueled micro-TPV power device [13] has almost the same configuration and dimension as the propane (C_3H_8)-fueled micro-TPV power device [12]. The results that show performance comparable to that of the hydrocarbon-fueled micro-TPV device demonstrate the feasibility of using NH_3–H_2 blends in practical micro power generation devices, implying the potential of partial NH_3 substitution to improve the safety of pure H_2 use with no carbon generation.

Although efficiencies could not be a critical parameter of the TPV performance for the specific applications, e.g., the military applications, it is obvious that enhancing the overall system efficiency will be helpful to reduce operating costs, considering that the recent studies of the micro-TPV devices show the overall efficiency in the range of 0.05–2.3% [4,6,8,12,13]. In fact, the heat-recirculating micro-emitter for enhancing the overall system efficiency with stable burning has been developed in this laboratory [10,12,13]. Since the micro-emitter that applies the heat-recirculation concept just recovers the exhaust heat, however, additional improvements can be possible if the conductive and convective heat losses from the micro-emitter walls, except for radiation to PVCs (photovoltaic cells), are reduced or utilized for the overall system. Meanwhile, the concept that H_2 is produced by

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http://dx.doi.org/10.1016/j.energy.2014.06.053
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Please cite this article in press as: Um DH, et al., Power and hydrogen production from ammonia in a micro-thermophotovoltaic device integrated with a micro-reformer, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.06.053

burning and reforming NH_3 in a micro reforming system has been also demonstrated in this laboratory [14]. Ammonia was reformed in the micro-reformer and also burned in the micro-combustor as a heat source. Thus, if the micro-TPV device using the heat-recirculating micro-emitter is integrated with the micro-reformer that also requires a heat source for the reforming process, the overall system efficiency is expected to be enhanced compared with that when the micro-TPV device operates alone. Still, no carbon is generated since NH_3 and H_2 are used for both the micro-emitter and the micro-reformer.

In view of the above considerations, it is of interest to evaluate the potential of integrating a micro-TPV device with a micro-reformer, using NH_3–H_2 blends as a carbon-free fuel. Thus, in the present investigation we aim to design the NH_3–H_2 blend-fueled micro-TPV power device integrated with the micro-reformer that converts NH_3 to H_2 by using the conductive and convective heat from the micro-emitter in the micro-TPV device and demonstrate its performance with the following specific objectives. The first objective is to measure the performance of the micro-emitter for the micro-TPV power device that applies the novel configuration optimized for the NH_3–H_2 blends (e.g., installation of cyclone and helical adapters), which was suggested from the earlier study in this laboratory [13]. The second is to measure the performance of the micro-TPV device that includes the micro-emitter and the PVCs. The third is to measure the TPV performance when a micro-reformer is integrated with the micro-TPV device. The effects of the existence of the micro-reformer on the temperature distribution of the micro-emitter, emissive and electrical power and the TPV system efficiency are observed. The fourth is to evaluate the overall performance of the micro-TPV device integrated with the micro-reformer. Finally, we identify the optimal operating conditions from the observations and determine if the overall efficiency is remarkably enhanced compared with that when the micro-TPV device operates alone.

The present discussion begins with descriptions of experimental methods. Results are then considered, treating the performance of the micro-emitter, the micro-TPV device (including the micro-emitter), the micro-TPV device integrated with the micro-reformer and the optimal operating conditions, in turn.

2. Experimental methods

A diagram of the present experimental apparatus is given in Fig. 1. The set-up consists of a test micro-TPV device integrated with a micro-reformer, a gaseous NH_3–H_2-air mixture supply system, a gaseous NH_3 feed system, thermocouples (K-type: a bead diameter of 250 ± 20 μm with an accuracy of ±0.05%) and an infrared camera (Flir T335: 253–2273 K with the resolution of 0.05 K) for measuring the temperature distributions on the surfaces of the micro-emitter outer walls and the PVCs, a spectrometer (Aspec 2048L/Nir256-2.5: 300–2500 nm) for measuring the spectral distribution of the micro-emitter walls, a digital camera (Sony A65) for recording the radiating micro-emitter images, a multimeter (Hioki 3803: 0.4000–40.00 V with an accuracy of ±0.6% and 0.4000–10.00 A with an accuracy of ±1.5%) for measuring the electrical output characteristics of the PVCs, a gas (nitrogen oxide (NO_x) emissions) analyzer (Testo 350-XL: an accuracy of 0.1–1.0 ppm) and a GC (gas chromatography, Clarus 500) system and a bubble meter for measuring the composition of reformed gas and the production rate of the reformed gas $\dot{m}_r$.

A micro-emitter of the micro-TPV device is surrounded by the catalyst-charged micro-reformer that is again surrounded by a chamber, the inner and outer walls of which have installations of PVCs and cooling fins. The micro-reformer is uninstalled when the performance of the micro-TPV device alone is measured, which will be discussed in Section 3. The combustible mixture and NH_3 are delivered to the micro-emitter and the micro-reformer by commercial mass flow controllers (Teledyne Hasting Instruments and Alicat Scientific: 1–10,000 sccm) with an accuracy of ±0.75% of full-scale. The controllers are managed by PC-based software (LabVIEW) that enables independent control of mixture micro-emitter inlet velocity V and composition (fuel-equivalence ratio ϕ and the mole fraction of H_2 in the fuel gas $x_h = X_{H2}/(X_{NH3} + X_{H2})$ where X_{NH3} and X_{H2} are the mole fractions of NH_3 and H_2) and the feed rate of NH_3 $\dot{m}_f$. The NH_3–H_2-air mixture is delivered into the annular micro-emitter inlet through a cyclone adapter and a helical adapter with the twist angle $\theta = 20°$ to enhance the residence time of the fed mixture and uniform burning, which was developed for NH_3–H_2 blends in the earlier study from this laboratory [13].

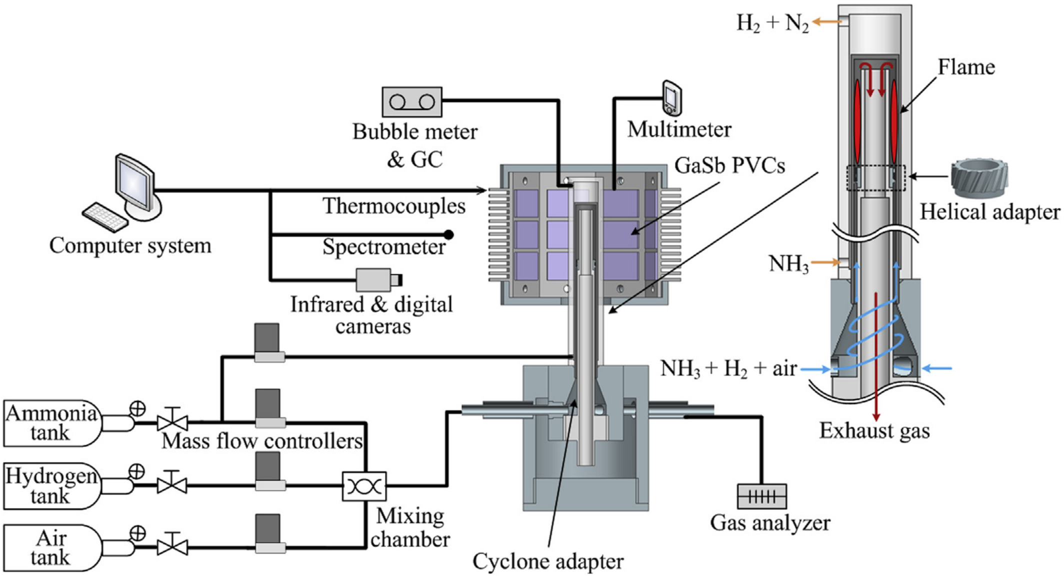

Fig. 1. Schematic of experimental apparatus.

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