Available online at www.sciencedirect.com

SciVerse ScienceDirect

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

Performance of a micro-thermophotovoltaic power system using an ammonia-hydrogen blend-fueled micro-emitter

S.I. Lee [a,b], D.H. Um [a], O.C. Kwon [a,*]

[a] School of Mechanical Engineering, Sungkyunkwan University, 2066 Seobu-ro, Jangan-gu, Suwon, Gyeonggi-do 440-746, Republic of Korea

[b] Hyundai Dymos Inc., Hwaseong, Gyeonggi-do 445-110, Republic of Korea

ARTICLE INFO

Article history:
Received 26 November 2012
Received in revised form
2 May 2013
Accepted 4 May 2013
Available online 15 June 2013

Keywords:
Thermophotovoltaic
Micro-emitter
Hydrogen
Ammonia
Heat recirculation

ABSTRACT

The potential of ammonia (NH_3)-hydrogen (H_2) blends as a carbon-free, green fuel in a 1–10 W micro-thermophotovoltaic (micro-TPV) device is evaluated experimentally. When NH_3–H_2 blends are used directly (without any modification) in a heat-recirculating micro-TPV configuration that has an installation of gallium antimonide (GaSb) photovoltaic cells and was developed for hydrocarbon fuel, low temperature on the micro-emitter outer surface is observed, generating a secondary flame at the micro-emitter outlet. Thus, the micro-TPV device has been modified to eliminate the secondary flame by enhancing the residence time of fed NH_3–H_2–air mixtures and uniform burning: a cyclone adapter for a fuel-air mixture supply system and a helical adapter for the fuel-air mixture upstream of the micro-emitter. Under optimized design and operating conditions, the micro-TPV device produces 5.2 W with an overall efficiency of 2.1% and an emitter efficiency of 37%, indicating the maximum temperature of the micro-emitter outer surface up to 1408 K. Thus, the feasibility of using NH_3–H_2 blends in practical micro power-generation devices has been demonstrated, implying the potential of partial NH_3 substitution to improve the safety of pure H_2 use with no carbon generation.

1. Introduction

Combustion-driven miniature or micro-scale (which will be referred to as *micro* hereafter) power systems have been considered as one possible alternative to replace current lithium-ion batteries due to their expected benefits such as quick fuel charge and high mass-based energy density [1]. Among others micro-thermophotovoltaic (micro-TPV) devices are expected to be easily scalable for micro-power generation due to their simple structure without moving parts. Particularly, the micro-TPV power devices are practical for the military applications (e.g., portable electronics for foot soldiers) where the weight, volume and charging time (rather than the system efficiency) of the power sources could be the critical performance parameters. Thus, several micro-TPV systems, including micro-emitters (micro-combustors), have been recently developed [2–12]. For the combustion-driven TPV systems hydrocarbon fuels were generally used because of practical considerations such as transport and storage [6–12]. Since they produce a greenhouse gas, carbon dioxide

* *Corresponding author*. Tel.: +82 31 290 7465; fax: +82 31 290 5889.
E-mail address: okwon@skku.edu (O.C. Kwon).

0360-3199/$ – see front matter
http://dx.doi.org/10.1016/j.ijhydene.2013.05.010

(CO_2), however, alternative fuels can be considered for the micro-TPV devices. Hydrogen (H_2) is one of the possible candidates and it was actually used for prototype micro-TPV power generators in some previous studies [2–4]; however, its practical use for micro-combustors is questionable due to the fuel storage problem.

Ammonia (NH_3), containing hydrogen and being easily liquefied, can be considered as a clean H_2 carrier since it can be easily transported and stored and on-site reformed to H_2 via the carbon-free process [13]. Also, NH_3 with additives or catalysts can be burned directly in combustion devices. Recently, the potential of partial NH_3 substitution to improve the safety of H_2 use with no carbon generation has been evaluated in this laboratory [14–16]. Also, the concept that H_2 is produced by burning and reforming NH_3 in a micro reforming system has been demonstrated [17].

In view of the above considerations, it is of interest to evaluate the potential of NH_3–H_2 blends as a carbon-free fuel in a micro-TPV device. Thus, in the present investigation we aim to demonstrate the performance of the NH_3–H_2 blend-fueled micro-TPV power device with the following specific objectives. The first objective is to observe if the NH_3–H_2 blends can be directly used for the micro-TPV power device that applies the novel configuration suggested from the earlier studies in this laboratory [10–12]. We conduct experiments for the proper NH_3–H_2–air mixture composition and injection velocities that are determined from the earlier fundamental studies of NH_3–H_2–air flames [14–16]. The second is to modify the micro-TPV configuration for obtaining reasonable performance and construct a micro-TPV power device that is optimized for the NH_3–H_2 blends. The third is to observe the effects of new design parameters on the performance of the modified micro-TPV power device. We properly determine the new design parameters for optimizing performance as well as the length of the micro-emitter for maximizing the heat-recirculation effects. Finally, we identify the optimal design and operating conditions from the observations when photovoltaic cells (PVCs) are installed.

The basic configuration of the micro-TPV device for hydrocarbon fuel and its performance for NH_3–H_2 blends, the modified micro-TPV configuration for the NH_3–H_2 blends and its performance, the effects of new design parameters on the performance of the modified micro-TPV device, and the optimal design and operating conditions will be subsequently presented, following the specifications of the experimental methods used during this investigation.

2. Experimental methods

Fig. 1 shows a diagram of the experimental apparatus that consists of a test micro-TPV device, a NH_3–H_2–air mixture supply system, thermocouples for measuring the temperature distribution on the outer wall surfaces of a micro-emitter and PVCs in the micro-TPV device, a multimeter for measuring the electrical output of the PVCs, and a digital camera (Sony A65) for recording the radiating micro-emitter images.

The combustible mixture is delivered to the micro-emitter using commercial mass flow controllers (Teledyne Hasting Instruments and Alicat Scientific: 20–4000 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 volume flow rate (micro-emitter inlet velocity V) and composition (fuel-equivalence ratio ϕ and the mole fraction of H_2 in the fuel gas $x_h = X_{H_2}/(X_{H_2} + X_{NH_3})$ where X_{H_2} and X_{NH_3} are the mole fractions of H_2 and NH_3, respectively). The NH_3–H_2–air mixture is delivered into the annulus through beads to obtain uniform flow at the micro-emitter inlet or through cyclone and helical adapters to enhance the residence time of the fed mixture and uniform burning. The beads are used first for the basic configuration of the micro-TPV device that was developed for hydrocarbon fuel in the earlier studies from this laboratory [10–12] and then the cyclone and helical adapters are used for the modified configuration of the micro-TPV device for the NH_3–H_2 blends. The detailed configurations of the designed adapters are discussed in Section 3.3. K-type thermocouples (a bead diameter of 250 ± 20 μm) with an accuracy of ±0.05% are used to measure the temperature distributions on the surfaces of the micro-emitter outer walls and the PVCs. This measurement of the surface temperature may have the reduced accuracy due to the imperfect contact between the thermocouple and the surface since the thermocouples are mounted directly on the micro-emitter and PVC surfaces. Thus, final results were obtained by averaging measurements of 4–5 tests at each location and their typical variation was 10 K. Using 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%), the electrical output characteristics of the PVCs are determined.

The micro-emitter is a simple cylinder with an annular-type shield to adopt a heat-recirculation concept. The outer wall of the broadband emitter for the micro-TPV device is made of silicon carbide (SiC) since it has high thermal conductivity, emissivity and temperature reliability [18]. Fig. 1 shows the micro-emitter configuration and the major dimensions, which are determined from the earlier study of the micro-TPV device for hydrocarbon fuel [12]. When the configuration of the micro-emitter is modified for NH_3–H_2–air mixtures, it is needed to visualize the flame inside the micro-emitter; thus, the SiC tube is replaced by a quartz tube. The micro-emitter is surrounded by an octagonal-tube-shaped chamber, the inner and outer walls of which have installations of PVCs and cooling fins, respectively (also shown in Fig. 1). Gallium antimonide (GaSb) cells (JX Crystals Inc.) that have reasonable quantum efficiencies (0.5–0.8) in the 0.7–1.8 μm wavelength [19] are used to provide high power density and efficiency for the present SiC micro-emitter. Their nominal efficiency is 10% with the operating limit temperature of 500 K. The 16 single bus PVCs are attached on the inner walls of the chamber that surrounds the micro-emitter, being connected electrically in series. As a heat sink for the PVCs the aluminum cooling fins with the length l_c = 9.0 mm are installed on the outer walls of the chamber. The detailed configuration and materials of the designed micro-TPV device are discussed in Section 3.1. A flame in the micro-emitter is obtained by establishing an injected, cold flow of reactive mixture that is then ignited at the exhaust outlet by a spark. Once the mixture is ignited, the flame moves backward and is stabilized in the micro-emitter.