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THE DEVELOPMENT OF TUBULAR PLATINUM-EMITTER REACTOR FOR A SMALL-SCALE THERMOPHOTOVOLTAIC POWER SYSTEM

Yueh-Heng Li[1,2], Jing-Ru Hong[1]

[1] Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan, 701, Taiwan, R.O.C.

[2] Research Center for Energy Technology and Strategy, National Cheng Kung University, Tainan, 701, Taiwan, R.O.C.

Abstract

This paper centers on the development of a micro-scale combustion-driven thermophotovoltaic (TPV) power generation system. The Micro-TPV system is a direct energy conversion device. It does not have any moving parts, and it converts the thermal power to electrical power directly. In this thesis, the first task is to design a combustor as an emitter for TPV power system. The characteristics of the combustor are to use catalyst tube with specific configuration and fuel/air mixture deployments to overcome the shortcomings of combustion instability and radical termination in a small-scale confined channel. Backward-facing step and perforated platinum tube are employed in a small-scale combustor to enhance flame stabilization and extend stable flammability. The stable operating range of the proposed tubular combustor is also verified.

Keywords: *thermophotovoltaic, platinum, emitter, combustion-driven.*

1. Introduction

Thermophotovoltaic (TPV) is a direct heat to electricity conversion approach, and the TPV conversion concept is straightforward. Thermal or infrared radiation is converted by a photovoltaic (PV) cell into electricity, and it is analogous to solar radiation converted by a PV cell into electricity. Compared to solar PV, TPV has two advantages. One is that TPV conversion is applicable to any high temperature heat source including the solar, combustion, nuclear and waste heat sources. Accordingly, using combustion to generate thermal radiation is considered as combustion-driven TPV system. The second benefit is that the efficiency can be enhanced by the control of the absorbed spectrum in the PV cell compared to solar PV. Nevertheless, combustion-driven TPV power generator is one of promising approaches to simultaneously harvest electric power and heat output. Because it does not involve any moving parts, its fabrication and assembly are relatively simple and easy. Research interest in combustion-driven TPV power generator has received intensive attention recently. Chou *et al.* (2014) designed a small-scale combustor with SiC porous medium and engaged in TPV system with the benefit of uniform thermal radiation. Li *et al*. (2010, 2011a, 2011b) attempted to convert flame radiation into electrical output via photovoltaic cells, to add iron pentacarbonyl into liquid hydrocarbon fuels for enhancing flame radiation and to coat metal oxide layer on a quartz tube for improving radiant efficiency. Li *et al.* (2009) and Yang *et al.* (2002) proposed a hydrogen-fueled micro-TPV combustor, and used backward facing step as flame stabilization mechanism. Besides, Yang *et al.* (2005) tested different emitting materials for enhancing radiant efficiency. Ferrari *et al.* (2014) outlined the current state-of-the-art of TPV system, and assessed the energy conversion of each component in TPV system.

Undoubtedly, the high surface-to-volume ratio of a small-scale combustor could lead to increasing heat loss to the surroundings and the possibility of radical termination on the wall. These effects may greatly reduce flame stability and fuel conversion efficiency in a small-scale combustor. In order to extend the stable

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operating range of a small-scale combustor, the utilization of quenching-resistant fuel, such as hydrogen (Zarvandi *et al.*, 2012), and catalytic materials (Li *et al.*, 2012), such as noble metals, in a small-scale TPV system has been considered as a promising manner to alleviate the above mentioned shortcomings. Since catalytic material is an important reaction enhancer for small-scale combustor, a novel concept is proposed here to use platinum, a noble metal, as the catalyst and the emitter for the small-scale TPV system. Besides, platinum is not only a catalytic material, but also a selective material (Yang *et al.*, 2005). The spectrum of illumination from platinum is prone to congregate in shorter wavelength region due to its larger emissivity in this region. Furthermore, it is much easier to manufacture a platinum emitter than the other selective emitters such as micro-machining tungsten and rare-earth oxide. For the quenching-resistant property, hydrogen is a promising fuel candidate for small-scale TPV power system due to its inherent large thermal diffusivity and high sticking coefficient to catalyst. Furthermore, hydrogen is a high-energy-density and quenching-resistant fuel. Therefore, hydrogen is a candidate for applying in micro-TPV power system. Platinum tubes are often used as a catalyst for hydrogen-fueled small-scale combustors [Volchko *et al.*, 2006]. However, the low volumetric energy density of hydrogen leads to the small-scale combustor that has to be operated at high fuel mass flow throughout. The high mass flowrate would further reduce the residence time for flame stability and complete combustion. Therefore, the flame-stabilizing mechanism is a pivotal consideration in small-scale combustor design.

In a small-scale channel, the mechanism of flame stabilization is strongly related to combustion efficiency and operational range. Akram and Kumar (2011) experimentally investigated combustion behaviors of methane-air mixture in meso-scale diverging channels, which showed an enhancement of flame blow-off limit compared to the plain channel. Wan *et al.,* (2015) implemented a wall cavity in a micro channel to extend the flame blow-off limit of H_2-air combustion. Li *et al.* (2012) applied the cavity flame holder to micro-channels with segmented catalyst on the inner walls. Nonetheless, non-uniform illumination of the emitter and reduced overall efficiency of TPV system are usually related to using improper flame stabilizers in a micro channel. Therefore, in the present study, a novel combustion chamber design is originated from the concept of our previous study with regard to segmented catalyst with cavity in a channel. In order to apply this concept to combustion-driven TPV system, a platinum tube with perforated-hole array is proposed and used as catalyst, emitter, and flame stabilizer to overcome the critical heat loss and to improve the flame instability. Concept, design, and demonstration of the small-scale tubular platinum combustor with perforated-hole array for future application in a small TPV power generation system are addressed and discussed in this paper.

2. Conception of the small-scale combustor

In our previous paper (Li *et al.*, 2012), applying segmented catalysts with cavities in a channel can integrate advantages of homogeneous and heterogeneous reactions, and enhance fuel conversion. The heterogeneous reaction in a prior catalyst segment produces chemical radicals and catalytically induced exothermicity, and homogeneous reaction can be subsequently ignited and anchored in the following cavity. The presence of cavities appreciably extends the stable operational range of the micro-reactor for a wide range of inlet flow velocities. To demonstrate and verify the above mentioned concept that is feasible in a small-scale TPV combustor, a preliminary numerical simulation is performed prior to experiments. A commercial code, CFD-ACE+, is modified to incorporate the detailed gas-phase and surface reaction mechanisms in CHEMKIN formats for the simulation. For simplicity, the small-scale combustor is modeled as a two-dimensional system. The platinum tube has two segments, 4.5 mm and 24.5 mm long, respectively, as shown in Fig. 1. The distance between segmented tubes is 1 mm. The dimension of segmented platinum tube is 5.3 mm in inner diameter and 6 mm in outer diameter, and the dimension of quartz tube is 8 mm in inner diameter and 10 mm in outer diameter. Accordingly, the area of cross section for inner tube and annular tube are approximate. The total length of the reaction channel is 30 mm long. The inner and outer equivalence ratios of the hydrogen-air mixtures are 0.3 and 0.6, respectively. The inlet temperature is 300 K. A uniform velocity profile is specified at the inlet and the flow velocity is fixed at 20 m/s for the platinum tube with and without segmentation. At the exit, pressure is specified with a constant ambient pressure of 101 kPa and an extrapolation scheme is used for species and temperature.

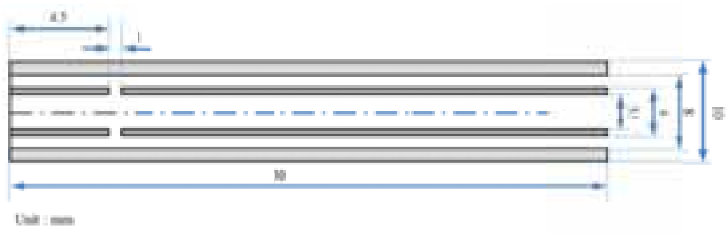

Fig. 1: Schematic diagram of segmented platinum tube for numerical simulation.

Chemical reaction mechanisms are used in the gas phase as well as on the catalyst surface. The homogeneous reaction mechanism of hydrogen-air combustion composes of 9 species and 19 reaction steps; these are adopted from the mechanism proposed by Miller and Bowman [1989]. The surface reaction mechanism is compiled primarily from that proposed by Deutschmann et al. [1996]. These reaction mechanisms have been used in previous studies and the comparisons with experimental results are satisfactory [Chen *et al.*, 2006].

Figure 2 compares the computed H_2 and OH mass fractions in both catalyst configurations. As to the conventional plain platinum tube, H_2 at the inner surface is initially reacted heterogeneously and provides catalytically induced exothermicity to assist hydrogen conversion at the outer surface, as seen in lower panel of Fig. 2. The overall fuel conversion rate of the conventional plain platinum tube is 83.8%. According to the computed OH mass fraction, the catalytically induced combustion is anchored on the outer catalyst surface. However, the anchoring position of gas-phase reaction is strongly related to the inlet condition in a conventional plain platinum tube. As to the segmented platinum tube, the distance for completion of hydrogen conversion is shorter than that in a conventional plain platinum tube. The overall fuel conversion rate of the segmented platinum tube is 95.2%. The gas-phase reaction is anchored on the gap between two tubes, as seen in the upper panel of Fig. 2. It appears that the gap between two tubes can enhance the flame stabilization by means of providing a low-velocity zone as well as collecting heat and chemical radicals from both sides. Consequently, the distribution of different equivalence ratios of fuel/air mixtures along both sides of catalyst surface can mutually assist heterogeneous and homogeneous reactions in a confined space, and hence prevent heat loss to the tube wall. The preliminary computation confirms that the proposed concept is applicable to a small-scale perforated-platinum combustor.

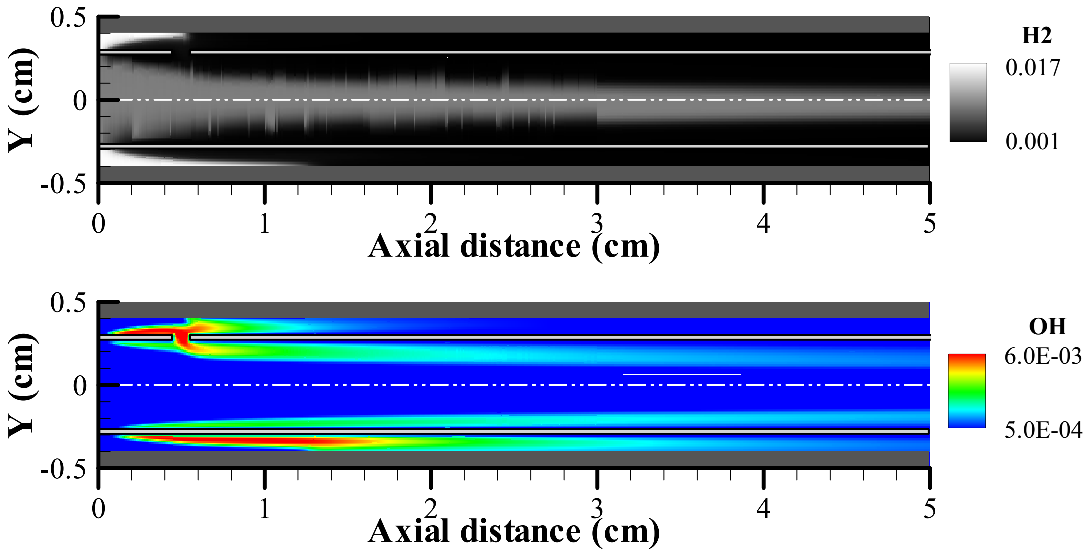

Fig. 2: Comparison of the computed contours of H_2 and OH mass fractions for the platinum tube with and without segmentation. The inner and outer equivalence ratios are 0.3 and 0.6, respectively, with the inlet velocity fixed at 20 m/sec.

3. Experimental apparatus

In order to realize the concept of segmented platinum tube in a confined channel, a small-scale platinum tube with perforated-hole array is designed in this study. The function of perforated-hole array is to simulate the gap between two platinum tubes. Figure 3 shows the schematic diagram of the proposed platinum combustion chamber with perforated-hole array and its corresponding pipes. The dimension of the platinum tube is 5.3 mm in ID, 6 mm in OD, and 30 mm in length with six perforated holes (1 mm in diameter) equidistantly placed around the tube at 5 mm away from the bottom of the platinum tube. The platinum tube is connected with a stainless steel tube with 1 mm in ID and 2 mm in OD. It makes a backward-facing step, which of length is 5mm, in the connection section. The platinum tube is confined in the quartz tube, which has a diameter of 8 mm in ID and 10 mm in OD. Hydrogen, utilized as fuel, and air are metered with electronic flowmeter (Brooks, 5850E) and calibrated in the range of 0-20 standard l/min. The pre-chamber filled with steel wool can provide a space to mix the fuel/air, as shown in the right hand-side of Fig. 3. Well premixed fuel/air mixtures with different equivalence ratios are separately delivered to the inner and outer tubes. The Reynolds number ranges from 377 to 1258 in the experiments. Therefore, the flow is assumed to be in laminar regime. In this study, two different platinum tubes, the conventional plain and perforated platinum tubes, are employed in the experiments to investigate the effects of fuel/air distribution and inlet flow velocity on the performance of the small-scale combustor. Figure 4 shows the experimental setup. A digital camera is used to record the combustion phenomenon in the combustor. For the irradiance measurement, the platinum combustor has to place inside the integrating sphere and the resulting radiant intensity is measured by the spectrum meter (Oceanoptic, USB2000+XR1), which has a uniform quantum efficiency ranging from ultraviolet (200 nm) to near-infrared (1050 nm) wavelength region. Various fuel/air mixtures are separately deployed and delivered to outside and inside of the tube, and the combustion phenomena of two platinum tubes are individually recorded via a digital camera. For monitoring temperature distribution and radiant intensity of two platinum tubes, an infrared thermal camera and a radiometer are used and recorded via a computer.

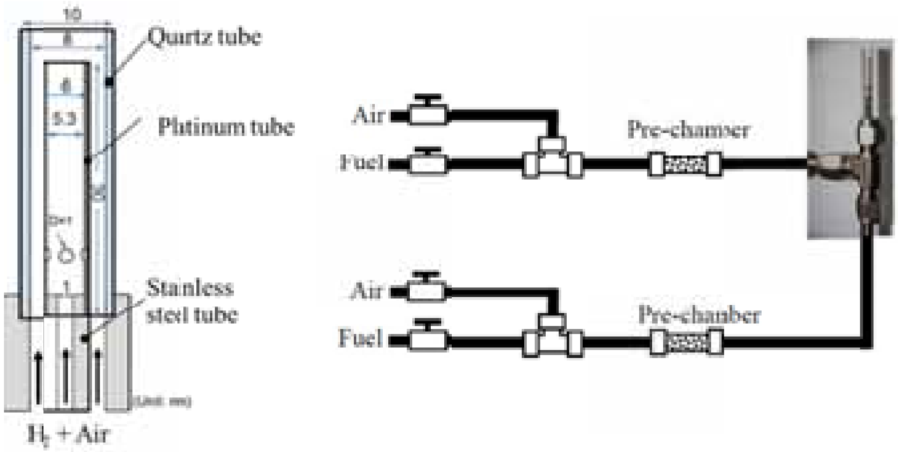

Figure 3: Schematic diagram of the platinum combustion chamber with perforated hole array and the corresponding pipes.

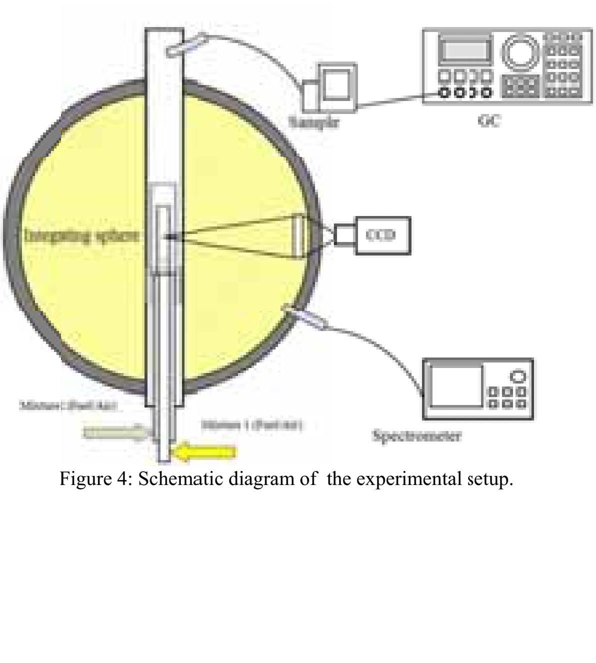

Figure 4: Schematic diagram of the experimental setup.

4. Results and discussion

Figure 5 shows the photograph of combustion phenomenon for two combustor cases under fixed fuel/air equivalence ratios and various inlet velocities (V = 5 and 10 m/s). The stream of ER = 0.6 mixtures is prone to induce both heterogeneous and homogenous reactions, while the ER = 0.3 stream induces only heterogeneous reaction. When ER_{in} = 0.3 and ER_{out} = 0.6, there is only heterogeneous reaction on the conventional plain platinum tubular combustor due to heat loss and the lack of flame stabilization mechanism, as shown in Fig. 5a. With the perforated-holes, the catalytically holding combustion can be seen on the tube (Fig. 5b). When the inlet velocity is increased to 10 m/s, the radiation from the two tubes becomes much brighter than the previous cases (Figs. 5a and 5b). This is due to that catalytically holding combustion can be induced and stabilized inside the combustion chamber under the flammable fuel/air condition. It is noted that there are bright illumination regions congregated in the downstream part of the conventional plain platinum tube under the condition of ER_{in} = 0.3 and ER_{out} = 0.6 (Fig. 5c). In principal, extensive hydrogen reaction on the outer surface of the catalyst can release large amount of catalytically induced exothermicity, which can sufficiently compensate the heat losses. Besides, when the inlet flow rate is further increased, the residual hydrogen can induce gas-phase reaction in the downstream of the platinum tubular combustor. As to the perforated platinum tubular combustor, it can be seen from Fig. 5d that flame is anchored on the perforated holes of the platinum tube. The presence of flame not only accelerates fuel conversion, but also heats up the platinum tube to become a bright emitter. Figure 6 displays the measured surface temperatures along the platinum tubes for the case of ER_{in} = 0.3, ER_{out} = 0.6 and V=10 m/s. The surface temperatures of the perforated-hole platinum tubular combustor are much higher than those of the conventional plain platinum tubular combustor. This is because that both heterogeneous and homogeneous reactions occur in the perforated platinum tubular combustor, but only heterogeneous reaction takes place in the plain platinum tubular combustor.

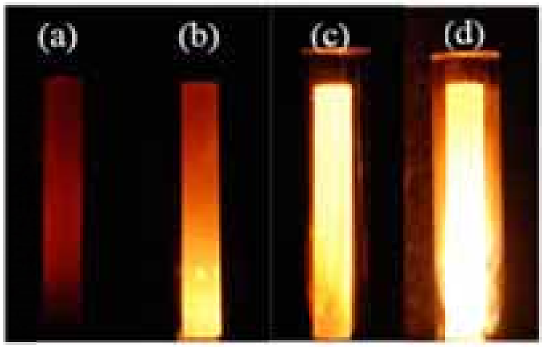

Figure 5. Photograph of combustion phenomenon for the cases: a conventional plain (a,c) and perforated platinum (b)(d) tubular combustor under the condition of ER_{in}=0.3 and ER_{out}=0.6 and various V=5 m/s (cases of a and b) and 10 m/s (cases of c and d). (The exposure time of photograph is fixed in 1/200 sec.)

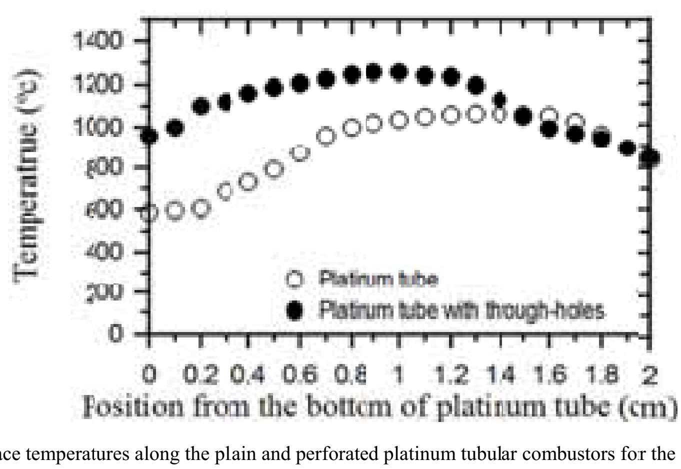

Figure 6. The measured surface temperatures along the plain and perforated platinum tubular combustors for the case of ER_{in} = 0.3, ER_{out} = 0.6 and V=10 m/s.

Figures 7 shows the operating range of the plain and the perforated platinum tubular combustors, respectively, with various fuel-air distributions under V = 10 m/s. Four distinct combustion phenomena, i.e., no illumination, heterogeneous reaction with dim red illumination, hetero- and homogeneous reaction with moderate illumination, and the combined hetero-/homo-geneous reaction with bright illumination, are identified by image observations and wall temperature measurements. For the plain platinum tubular combustor, conditions for bright incandescent illumination congregate in the higher inner and outer equivalence ratios (see Fig. 7a). The bright incandescent region is congregated in larger inner and outer equivalence ratios. The presence of backward-facing step in the conventional plain platinum tubular combustor primarily stabilizes the flame inside the tube, and heat loss from the tube can be reduced by means of heat release from catalytic induced exothermicity on the surface. Consequently, excessive fuel consumption in one side is necessary to sustain catalytically stabilized thermal combustion in the other side. Comparison of Figs. 7a and 7b indicates that the operating range with bright incandescent illumination for the perforated tubular combustor is much larger than that for the plain tubular combustor under the conditions of larger outer equivalence ratio. This is attributed to the presence of perforated holes for flame stabilization. The operating range of bright incandescent illumination for the perforated platinum tubular combustor is remarkably extended, especially for lower inner equivalence ratios. Regarding to the irradiance, the plain and perforated platinum tubular combustors are placed inside the integrating sphere connecting to spectrometer under the fixed equivalence ratios (ER_{in} = 0.3, ER_{out} = 0.6) and flow velocity (V=10 m/s). The measured irradiances are 18,052 W/m^2 for the conventional plain platinum tubular combustor and 19,858 W/m^2 for the perforated platinum tubular combustor.

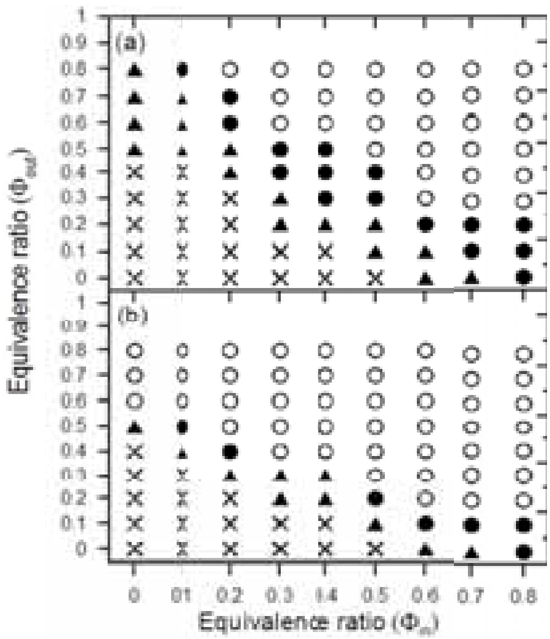

Figure 7. Operating range of a (a) plain and (b) perforated platinum tube under the condition of inlet flow velocity of 10 m/s. Symbols: (×) no illumination, (▲) heterogeneous reaction with dim red illumination, (●) combined hetero-/ homo-geneous reaction with illumination, and (O) hetero- and homogeneous reaction with bright illumination.

5. Conclusions

The result of a simplified simulation supports the concept of sustaining catalytic combustion on a platinum wall with a gap, and flames anchoring on the wall can contribute to efficiently heat up the wall temperature. For testifying the concept of our proposed micro-TPV combustor, an experimental study on the performance of the proposed perforated-platinum combustion chamber is made under various equivalence ratios and inlet velocities. Results demonstrate that the perforated-platinum tubular combustor can sustain the heterogeneous and homogeneous reactions, extend the operating range of the combustor, and enhance the incandescent illumination of the platinum tube. Besides, delivering fuel/air mixtures into two sides of platinum tube can reduce the heat loss from the chamber wall, and a perforated-hole can sustain flames anchoring on the wall in various flow velocities. These two novel approaches realize the application of simultaneously flame stability in a small-scale system and high illumination on the chamber wall. Therefore, the perforated-platinum tubular combustor can serve as an effective emitter for the small-scale TPV power generation system as compared to the plain platinum tube. These facts suggest that future application of the proposed concept and design of the perforated-platinum combustor to a small-scale TPV power system is feasible.

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