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Development of a tubular flame combustor for thermophotovoltaic power systems

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Abstract

A novel tubular combustor with a metal-oxide-deposited quartz emitter and a reversed tube is developed for application in a small thermophotovoltaic (TPV) power generation system. The tubular combustor employs asymmetrical injections of fuel and swirling air to enhance the fuel/air mixing in a short distance, and the resultant tubular flame provides an optimal thermal energy for the emitter. The tubular flame structures can be categorized into three modes: the double-layer flame, attached-wall flame, and strip flame. Only the attached-wall flame is preferable for application in a small scale TPV system. Experimental results indicate that the laboratory-made metal-oxide-deposited quartz tube has better performance than the conventional silicon carbide emitter. In addition, a reversed tube is implemented with the tubular combustor to redirect the hot product gas for reheating the tube wall. Therefore, the swirling flame is pushed back into the combustion chamber and leads to uniform illumination of the emitter. Consequently, the CO and NO_x emissions are significantly reduced and the radiant intensity is increased as compared to that of the emitter without a reversed tube.

Keywords: Mesoscale combustor; Metal oxide; Porous medium; Thermophotovoltaic (TPV); Tubular flame

1. Introduction

Mesoscale combustion has been considered as a potential solution for many small-volume, energy demanding systems, such as power supplies for portable devices [1,2] and propulsion units for small spacecrafts [3,4]. Among the energy conversion systems, the TPV system is a practical and feasible approach to directly convert radiation into electrical power [5,6]. With large energy density of hydrocarbon fuels (~50 MJ/kg), the combustion-driven small scale TPV power systems remain competitive with the contemporary lithium batteries (~0.6 MJ/kg), even if the overall efficiency of the combustion system is as low as few percents [7].

As the combustion volume is reduced, issues of residence time, fuel–air mixing, thermal management, and wall quenching of gas-phase reactions become increasingly more important. The flow residence time in a small-scale combustor may become less than the chemical time for a premixed combustion system, or less than the combined mixing and chemical times for a non-premixed

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system, thus rendering complete combustion in the chamber is a great challenge. The increasing surface-to-volume (S/V) ratio of a small-scale combustor not only results in increased heat loss to the wall, but also enhances the possibility of radical termination by wall reactions. Therefore, several well-known strategies, such as utilizing of quench-resistant hydrogen fuels [8], liquid–fuel-film combustor [9,10], thermal-recuperated Swiss-roll burner [11], or catalytic surfaces [12], were proposed to overcome these obstacles. On the contrary, the increase of surface-to-volume ratio in a TPV power system could also increase the relative contact face between the flame and the combustor wall and hence, to further enhance heat transfer ratio to the emitter wall. It is expected to increase the wall temperature of the emitter in spite of flame quenching.

In general, the materials of an emitter used in combustion-driven TPV system are ceramic and silicon carbide. The hardness of these materials makes them difficult to manufacture using conventional machining. Besides, these materials need more energy to heat up to incandescence condition due to their low thermal diffusivity, which is defined as the ratio of thermal conductivity to volumetric heat capacity. It implies that the hot flue gas is to burn closer to the emitter to more effectively deliver heat to the emitter wall for illumination. However, the flame tents to extinct when suffering from excessive heat loss and radical termination as the low thermal diffusivity wall moves closer to the flame. These unfavorable factors limit applications of conventional emitters in small-scale combustion-driven TPV power systems. In this paper, a novel tubular flame combustor, having advantages of high thermal diffusivity and easy-machining, is developed to overcome the above-mentioned difficulties. The combustor, made of quartz with metal-oxide deposits on the surface, is also used as the emitter for enhanced emissions in the visible range. Asymmetrical injections of fuel and swirling air are implemented to achieve adequate mixing and to perform the tubular flame in the quartz tube. Concept, design, and demonstration of the tubular-emitting combustor are addressed and discussed in the following sections.

2. Metal-oxide-deposited emitter and tubular flame combustor

In combustion of CO fuel, it may encounter the formation of red deposits on the combustor wall. The effect of red deposits on transparency of the quartz tube is shown in Fig. 1. Figure 1a and b show the quartz tube before and after exposure to CO-content flame, respectively. Analysis of the red deposits indicates that they are composed of iron and nickel oxide. Literature review reveals that the pressurized CO cylinders, even at high purity levels, contain up to 100 ppm of iron pentacarbonyl and somewhat smaller levels of nickel tetracarbonyl [13]. In fact, even in the process of producing CO, through steam reforming of natural gas or coal gasification, it also results in carbonyls contaminations [14,15]. It is interesting to note that the red deposits could not be removed by strong oxidant or acid. Metal-oxide particles seem to firmly embed in the quartz surface. Figure 2 shows the scanning electron microscope (SEM) image of the original quartz surface and that contaminated with metal oxide. The quartz tube contaminated with metal oxides will emit the radiant illumination as the flame exists inside the tube. Therefore, the metal-oxide-deposited quartz tube can be used

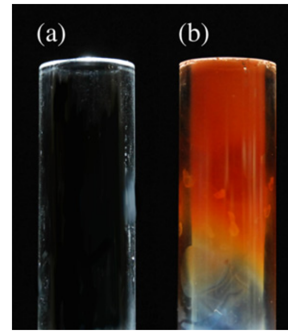

Fig. 1. Photograph of the quartz tube (a) without and (b) with metal-oxide contamination.

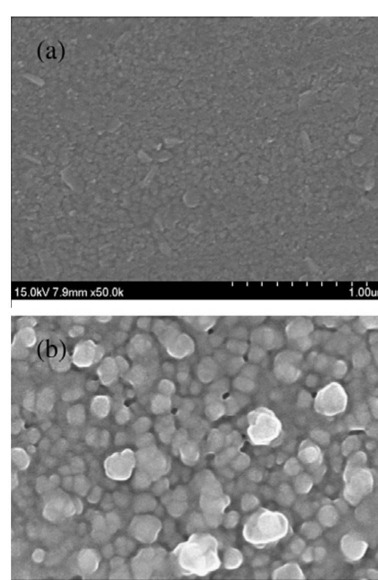

Fig. 2. SEM images of the surface of (a) quartz tube and (b) metal-oxide-deposited quartz tube.

as an emitter in a small-scale combustion-driven TPV system. In order to study the effect of materials on the performance of the emitter, an infrared thermal tube (SiC) and a metal-oxide-deposited quartz tube are tested. In the present study, the deposition of quartz tube with metal oxide is made by burning the methane fuel with iron pentacarbonyl. Iron pentacarbonyl is flammable and soluble in organic solvents, such as *n*-heptane. Therefore, it can be deposited in any shapes and any locations of the quartz tube.

In the design of a small-scale combustion-driven TPV system, a fully aerated flame burning closer to the emitter surface and heating up the surface to incandescence is necessary. It is expected that further increase of combustion gas temperature will considerably increase the useful radiation output. In order to stabilize an aerated flame burning along the tube wall in extensive operating range, a new tubular flame combustor is proposed in this paper. The tubular flame combustor consists of a main combustion chamber (inner diameter = 9.5 mm and length = 60 mm) with tangential air inlets. Methane is supplied through fuel ports with i.d. = 6 mm, as shown in Fig. 3. A porous medium, made of stainless steel, in the combustor is used to promote fuel/air mixing and stabilize the flame. It has a truncated conical shape of 4 mm diameter on the top, 6.5 mm diameter at the bottom, and 10 mm long. The pore size is approximately 20 μm. Fuels are allowed to flow into the chamber only through the peripheral porous surface. This type of fuel injection can be categorized as the asymmetric whirl concept [1]. In an asymmetric whirl, the fuel is injected off-axis to the swirling air flow in order to enhance fuel/air mixing. The flame is thermally stable because conductive heat loss behind the flame is negligible due to its symmetrical temperature distribution. The flame is also aerodynamically stable according to the Rayleigh stability criterion because the flow field consists of an inner burned gas region of low density and an outer unburned gas region of high density [16,17].

The combustor is designed as a conventional swirling combustor where a fully aerated swirling flame is stabilized in the combustor and burns closer to the combustor surface, which is the emitter. In order to attain a uniform emitter illumination, a heat-regenerating reversed tube is implemented with the tubular combustor. The main function of the reversed tube is to redirect hot product gas to reheat the outer surface of the emitter. Moreover, the existence of the reversed tube may also push the recirculation zone further into the chamber, which then forces the swirling flame to further cling to the wall. In this case, the emitter can attain thermal energy more efficiently by means of heat transfer from the flame as well as from the redirected hot product gas. The parameter, D, labeled in Fig. 3 defines the distance between the top of the reversed tube and the combustor exit. The reversed tube is made of quartz and has an inner diameter of 22 mm. There are four exit ports located at the bottom of the reversed tube for exhausting product gas.

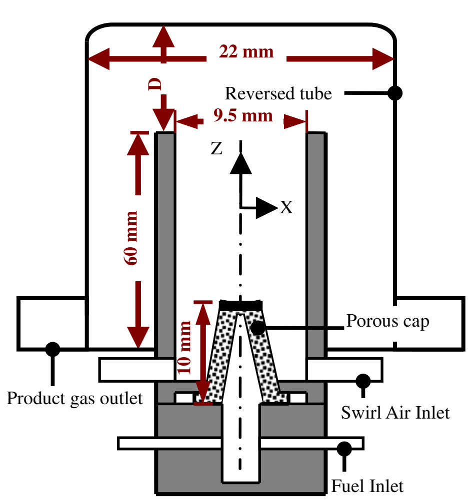

Fig. 3. Schematic diagram of the tubular combustor.

3. Results and discussion

3.1. Burner performance

Understanding the combustion characteristics of a tubular flame combustor is crucial for the design of a compact combustion-driven TPV system. Figure 4 exhibits the photographs of three combustion modes and Fig. 5 shows the mappings of stable flame regions corresponding to three combustion modes for various fuel flow rates. In the present study, flames would blow out or

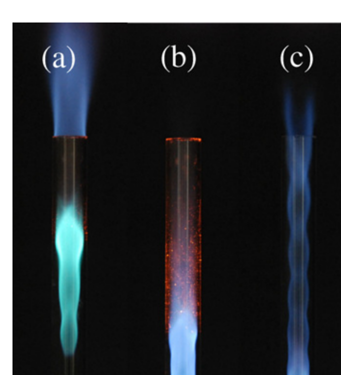

Fig. 4. Photographs of three tubular flame structures: (a) double-layer flame, (b) attached-wall flame, and (c) strip flame.

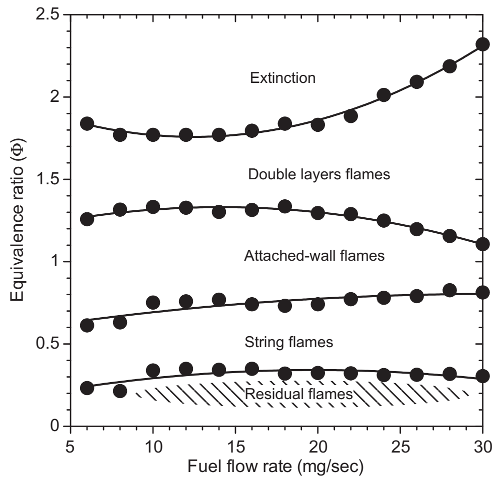

Fig. 5. Mapping of stable combustion region in the tubular combustor.

quench when air flow rates are too high, and flames would lift off and stabilize on the rim of the combustion chamber when air flow rates were too low. Between these extremes, there are three combustion modes existed over the range of operating conditions, including the double-layer flame, attached-wall flame, and string flame. The double-layer flame has a first flame anchoring along the combustion chamber and a second flame burning on the rim of the combustion chamber due to unburned gas reacting at the exit, and it appears in fuel-rich region. The anchoring position of the first flame is prone to the swirling effect, and the flame anchoring position tends to move upstream with increasing the air flow rates. Combustion of the first flame in double-layer flame mode is referred to the tribrachial flame and its flame base anchors in the boundary layer along the combustion chamber [18]. For the string flame mode, the flame with a stripe shape is segregated from the chamber surface and confined to the centerline of the combustion chamber due to strongly swirling air flow. The flame is stabilized in the recirculation zone close to the porous cap in fuel-lean regions and its flame stabilization is similar to inserting a bluff body in high-speed stream [19]. The porous cap is to be heated up by flames to the incandescence situation, and even in high-speed stream, there is still residual flame standing on the porous cap. These two combustion modes are not suitable for use in a radiant combustor because they do not heat the emitter wall effectively. For the attached-wall flame mode, the flame stabilizes on the porous cap so that the flame is insensitive to the change of the swirling air flow. This combustion mode meets the fundamental requirement of an emitter, due to the fact that the flame sheet attaches to the chamber wall. Figure 4b indicates the emitting characteristics of the quartz tube, which shows the flame effectively heating the combustor wall. The stable operating region of the attached-wall flame ranges from the fuel-rich to fuel-lean conditions, and the stable region becomes narrow with increasing the fuel flow rate, as shown in Fig. 5., The stable operating region of double-layer flame belongs to fuel-rich conditions, while that of string flame locates in fuel-lean region.

3.2. Radiation enhancement

The conventional emitter has high thermal conductivity and low thermal diffusivity, yet the radiation intensity of the emitter is proportional to its surface temperature. For instance, the thermal conductivity of silicon carbide is $100 \sim 140$ W/m K, which is higher than that of iron oxide ($5 \sim 10$ W/m K), so that it necessitates more thermal input for the silicon carbide tube to attain the high illumination condition. On the contrary, the metal-oxide-deposited quartz emitter possesses an advantage of the fast response to incandescence and uniform illumination feature due to its low thermal conductivity and high thermal diffusivity. Figure 6 shows the illumination feature of the tubular flame combustor with different emitter materials at the same fuel flow rate of 12 mg/s and stoichiometric condition. It appears that the emitter illumination of silicon carbide tube is not uniform and the bright illumination appears at the bottom of the emitter, which indicates the position of flame attachment. The illumination intensity of the metal-oxide-deposited quartz emitter is better than that of the silicon carbide tube, even though there is a spiral pattern emerging along the quartz tube.

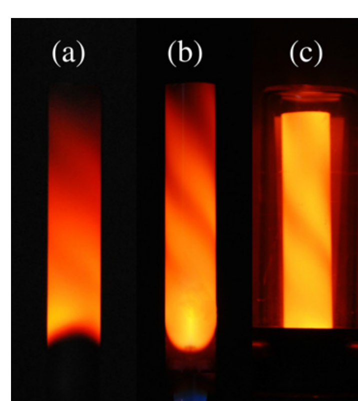

Fig. 6. Photographs of combustion chamber for (a) a silicon carbide emitter, (b) metal-oxide-deposited quartz tube without a reversed tube, and (c) with a reversed tube operated at fixed fuel flow rate (12 mg/s) and stoichiometric condition.

Uniform and high illumination intensity is essential for an emitter. The radiant efficiency of an emitter is strongly related to surface temperature of the emitter. Although the tubular flame can be stabilized inside the combustion chamber by swirling effect, the non-uniform illumination on the emitter may reduce the radiant efficiency and the overall performance of the small PTV power system. To ameliorate the non-uniformity of illumination, a heat-regenerating reversed tube is implemented with the tubular combustor to redirect the hot product gas for reheating the emitter. Figure 6c shows the improvement of the illumination intensity and uniformity on the quartz emitter by using a reversed tube. In order to quantify the illumination intensity and uniformity of the emitter, surface temperature along the emitter is measured by infrared thermometry as shown in Fig. 7. Figure 7a exhibits the temperature distribution along the surface of two different emitters for a fixed global equivalence ratio (ER = 1.0) and fuel input (12 mg/s). It can be seen that the surface temperature along the metal-oxide-deposited quartz tube ranges from 800 to 900 °C, which is about 100 °C higher than that of the silicon carbide tube. The sharp rise of surface temperature at 2.5 cm indicates the location of tubular flame attachment. By using a photometer, the measured overall intensity of the quartz emitter is 2.59 mW/min, which is slightly higher than that of the silicon carbide emitter (2.34 mW/min). Figure 7b compares the measured surface temperatures for the quartz emitter with and without a reversed tube. Apparently, a quartz emitter with a reversed tube has higher surface temperature than that without a reversed tube. The quartz emitter with a reversed tube has a uniform temperature around 940 °C. It is noted that the change of distance (D) between the top of reversed tube and the combustor exit does not significantly affect the illumination intensity in the same operating condition. The intensity of the quartz emitter with a reversed tube is 3.39 mW/min, which is higher than the case of without a reversed tube.

In order to study the effect of reversed tube addition on the tubular flame structure, direct photographs and OH^* chemiluminescence images are taken for a fixed global equivalence ratio (ER = 1.0) and fuel input (12 mg/s), as shown in Fig. 8. Figure 8 and b show the results for the chamber with and without a reversed tube, respectively. The pictures on the left-hand-side of Fig. 8a and b are the photographs of flames. For the case of without a reversed tube, the flame inclines to the center of the combustion chamber. On the contrary, the flame leans toward the combustor wall when a reversed tube is added to the combustor. The right-hand-side of Fig. 8a and b shows the OH^* chemiluminescence images, which are transformed by Abel deconvolution [20]. The locations of high OH^* emissions indicate the reaction zone of flames. Figure 8a shows that high OH^* intensity is confined at the center of the combustor and a small recirculation zone appeared near the combustor exit. While with a reversed tube, the recirculation zone is pushed further into the combustion chamber so that the flame is squeezed toward the combustor wall. Consequently, the flame burns along the wall and provides optimal thermal energy to the emitter, resulting in high and uniform illumination on the emitter surface.

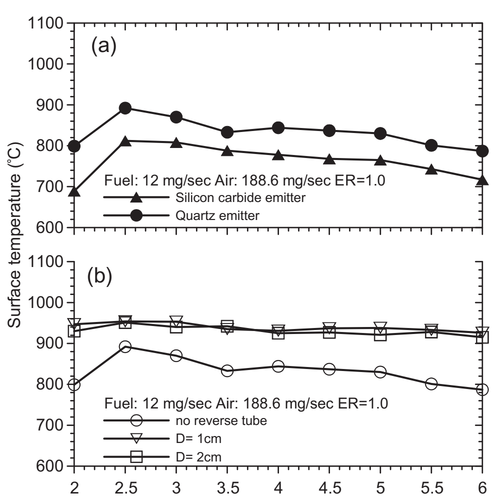

Fig. 7. Measured wall temperature distributions along the axial direction for (a) different emitter materials and (b) metal-oxide-deposited quartz tube with and without a reversed tube operated at fixed fuel flow rate (12 mg/s) and stoichiometric condition.

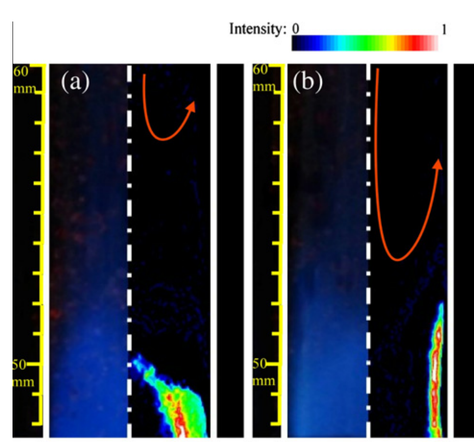

Fig. 8. Direct photographs and OH^* chemiluminescence images of the flame structures for the case of (a) without and (b) with a reversed tube.

Figure 9 shows the effect of reversed tube addition on CO and NO_x emissions under various global equivalence ratios. For the case of without a reversed tube, CO emission increases from 450 to 750 ppm when the global equivalence ratio is increased from 0.8 to 1.05. The corresponding NO_x emission increases from 40 to 60 ppm. For the case of with a reversed tube, CO emission is less than 100 ppm for the fuel-lean conditions. As the global equivalence ratio is increased from stoichiometric to fuel-rich condition, CO emission increases sharply and approaches to the case of without a reversed tube. An increase in the global equivalence ratio with a fixed fuel flow rate requires a decrease in the swirling air, which consequently reduces the swirling intensity. Low swirling intensity reduces the fuel/air mixing and leads to incomplete combustion. It is noted that the change of distance (D) does not significantly affect the CO and NO_x emissions. Moreover, the use of a reversed tube for the combustor operated at fuel-lean to stoichiometric conditions could significantly reduce the CO and NO_x emissions as compared to the case of without a reversed tube.

3.3. Emitter radiant characteristics

In order to examine the effect of emitter materials on the radiant intensity, the radiation spectra from the original quartz, metal-oxide-deposited quartz, and silicon carbide tubes are measured and compared in Fig. 10 for the stoichiometric condition. It can be seen from Fig. 10 that the high spectral intensity appears in the wavelength region from 600 to 900 nm for the metal-oxide-deposited quartz and silicon carbide tubes. The increase of the radiant intensity in visible wavelength region (350–600 nm) for the metal-oxide-deposited quartz tube probably comes from the flame luminosity, due to non-uniform deposition of metal oxide. For the original quartz tube, the radiation principally comes from methane flame luminosity and appears in visible wavelength region. Figure 10 clearly demonstrates that the metal-oxide-deposited emitter can radiate light from visible to near-infrared region and hence, this approach can improve the performance of the silicon-based PV system.

The overall performance of the developed tubular-emitting combustion-driven TPV power system is examined by measuring the radiant intensity from the emitters operated under various fuel flow rates. Figure 11 shows the measured radiant intensity from the silicon carbide emitter and the metal-oxide-deposited quartz emitter with and without a reversed tube. The powermeter has a uniform quantum efficiency ranging from ultraviolet (190 nm) to near-infrared (1100 nm) wavelength region. It can be seen that the radiant intensity of the quartz emitter without a reversed tube is slightly

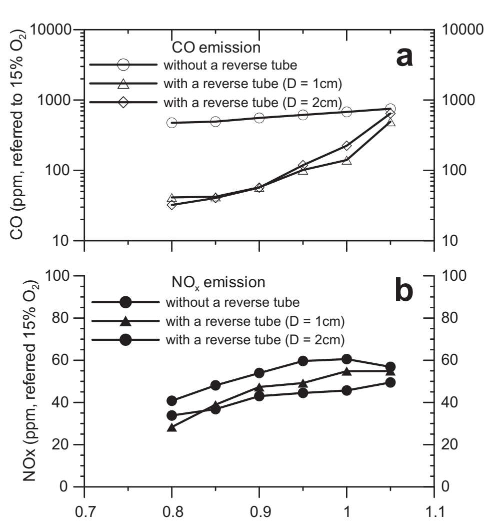

Fig. 9. Effects of global equivalence ratio and reversed tube on (a) CO and (b) NO_x emissions.

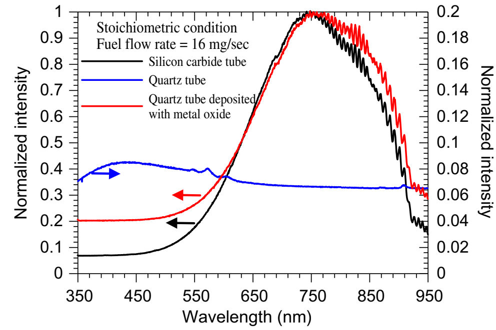

Fig. 10. Normalized spectral intensity from the original quartz, metal-oxide-deposited quartz, and silicon carbide tubes operated at fixed fuel flow rate (16 mg/s) and stoichiometric condition.

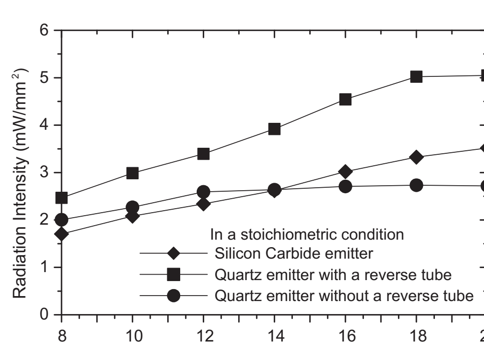

Fig. 11. Radiant intensity from the silicon carbide emitter and the metal-oxide-deposited quartz emitter with and without a reversed tube under various fuel flow rates.

higher than that of the silicon carbide emitter for the fuel flow rate less than 14 mg/s. As the fuel flow rate exceeds 14 mg/s, the radiant intensity of the silicon carbide emitter is higher than that of the quartz emitter due to extra fuel input overcame the large thermal diffusivity effect in silicon carbide emitter. For the case of with a reversed tube, the radiant intensity is much higher than that of two emitters without a reversed tube for the range of fuel flow rates studied. This fact clearly demonstrates that the replacement of silicon carbide emitter with metal-oxide-deposited quartz emitter as well as the addition of a reversed tube to the tubular combustor is a novel design of combustion-driven TPV power system.

4. Conclusions

A novel design of a tubular flame combustor with the metal-oxide-deposited quartz emitter and a reversed tube is demonstrated and tested in the present study. The developed tubular flame combustor can be applied to a mesoscale combustion-driven TPV system. Swirling combustion is adopted to increase the residence time, enhance fuel–air mixing, and stabilize the tubular flame in the miniature combustor. Three types of tubular flame structures are found, namely, the double-layer flame, attached-wall flame, and strip flame. Only the attached-wall flame is suitable for application in the TPV system. Experimental results indicate that the laboratory-made metal-oxide-deposited quartz tube has better performance than the conventional silicon carbide emitter. In addition, the implementation of the tubular flame combustor with a reversed tube leads to uniform illumination of the emitter, low CO and NO_x emissions, and high radiant intensity for a wide range of TPV operating conditions.

Acknowledgments

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