Research on Performance of Tubular MTPV System Combustor

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Abstract: Micro Thermophotovoltaic (MTPV) system is a new micro power Mechatronic system that converts thermal energy to electrical energy using thermal radiation property of material. Micro combustion chamber is the core part of this MTPV power system. When fuel is burnt in the micro combustion chamber, thermal energy is produced and then transferred to photovoltaic element through photons radiated by external wall of the micro combustor, and thus electrical energy can be exported. The temperature of external wall of micro combustor is the key standard measuring the conversion efficiency. By the test to analyze and describe the change of external wall temperature and radiation performance of tubular micro combustor when the factors including porosity, mixture ratio of CH_4/O_2, mixed gas flow and wall thickness of micro combustor are changed, the references are obtained for practical application of micro combustor and micro thermophotovoltaic system.

Keywords: micro thermophotovoltaic system; photovoltaic cell; porosity; tubular micro combustor

With continuous development and wide application of micro mechatronic system [1,2], new micro energy systems emerge out continuously. At present, most of products of micro mechatronic system are powered by battery, but the energy density of best lithium-ion battery is just 0.50MJ/kg. However, the energy density of hydrocarbon fuels can be up to 45MJ/kg approximately, and even if the energy conversion efficiency is 10%, the energy density provided by hydrocarbon fuels will be about ten times of normal battery [3,4]. Thus there are micro power energy systems emerging continuously.

1. Present Situation of Research on Micro Power System

1.1 Development direction of micro power system

Except the widely used charging battery system, the most important research direction of current micro power system involves the micro engine and micro generator system. Micro gas turbine engine [7,8] of Massachusetts Institute of Technology and micro Wankel engine [5,6,8] of University of California in America lead the research on micro engine system worldwide. The micro engine using hydrocarbon fuels has the advantages of low cost and stable power, but the size of parts is 10-100 μm, making it difficult to machine and assemble.

Micro generator directly converts chemical energy or thermal energy to electrical energy using special materials, and has the advantages of simple structure, capable of using various hydrocarbon fuels and working at room temperature. Structural schematic of "Swiss Roll" micro combustion chamber [4,9,10]. This kind of combustion chamber fully utilizes the heat exchange area to preheat the fresh gas, reducing thermal loss; it directly converts thermal energy to electrical energy using thermoelectric materials, overcoming the difficulties made by the machining and assembling of moving parts. However, its three-dimension geometry is complex, and thus electrochemical techniques are required to machine.

1.2 Generation of micro thermophotovoltaic system

Micro Thermophotovoltaic (or MTPV) power system is a new concept micro power system, which is developed from Thermophotovoltaic (TPV) energy conversion system.

It is a device that transfers thermal energy produced by hydrocarbon fuel combustion to photovoltaic cell using thermal radiation property and then produces elec-

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trical energy, shown in Figure 1 below. In recent years, because of the progress of low-energy band gap photovoltaic cell and high temperature resistant materials, the research on MTPV system gains people's attentions. Compared by the micro power device above, the most distinct feature is simple structure [8,11,12].

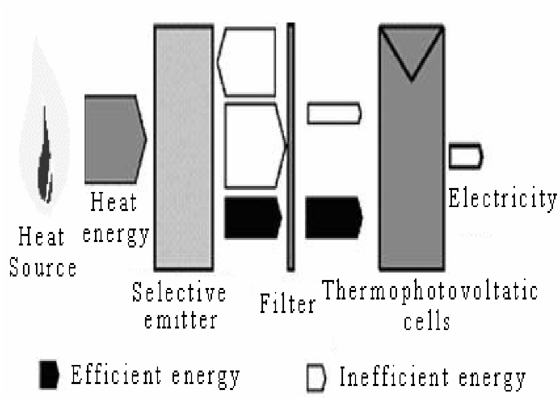

Figure 1 Schematic of Operating Principle of Micro TPV System

The research on Thermophotovoltaic (TPV) technology started from early 1960s. But in recent ten years, TPV system has been just built and applied as photovoltaic materials gain the breakthrough – converting lower quality thermal energy to electrical energy effectively. However, the application of TPV is limited to large and medium generators at present, with total efficiency of about 10%. As a kind of clean and squelch power supply, TPV system has many advantages: not containing any moving part, relatively easy manufacturing and assembling, high power density, and wide range of fuels, etc.

MTPV system is a miniature of TPV in dimension, with increased area/volume ratio. It can make better use of radiation produced by combusting heat to stimulate photovoltaic elements to generate electrical energy, and thus improve the efficiency of energy conversion. Because MTPV does not contain any moving part but has high energy density, it will be an ideal power source for portable electronic products and MEMS devices.

2. Principle and Operational Process of Micro Thermophotovoltaic Energy System

Main parts of MTPV system include premixer, micro combustor and photovoltaic (PV) element. Combustor has combustion chamber inside and radiator outside, and is the key part of system.

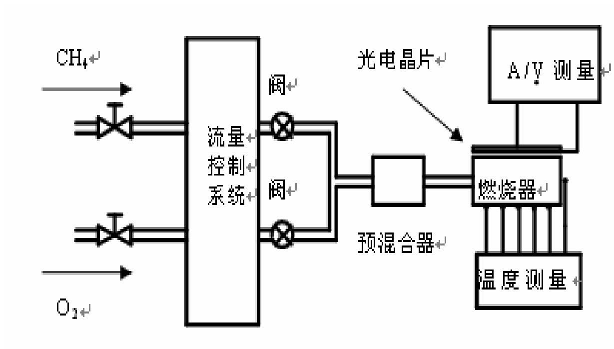

Figure 2 Schematic of Operational Process in Test

Schematic of operational process of MTPV system is shown in Figure 2 above. Fuels (hydrogen or hydrocarbon) and oxidant (oxygen or air) with certain a proportion are mixed in the premixer and then enter the micro combustor to burn. When the wall of selective radiation material is heated to some temperature, photons will be released. When these photons hit on the photovoltaic cell, free electrons will be activated and then electrical energy will be exported. Photovoltaic cells made of low frequency band gap materials are coated with a selective filter layer, which can make the photovoltaic cells absorb effective radiation produced by radiated materials and return the ineffective radiation, thus reducing the energy loss and improving the efficiency of photovoltaic conversion.

3. Performance Analysis of Micro Combustor

Because micro combustor and photovoltaic element are limited by micro machining techniques and materials, how to improve the performance of micro combustor is a top priority to be researched in the test. The tubular micro combustor selected in the test is shown in Figure 3 below. The tubular chamber of micro combustor is filled with small alumina ball to form a porous medium environment [14]. In the test, the used fuel is methane and combustion improver is oxygen, with environmental

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temperature of 285K.

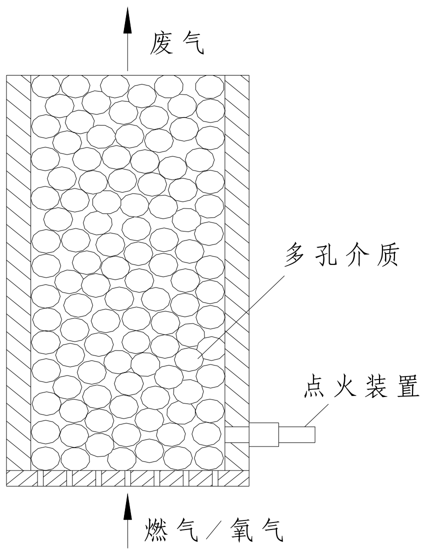


Figure 3 Schematic of MgO Ceramic Combustor

The porous medium environment quickens the combustion speed of mixed gas in the combustion chamber, and thus makes most of fuels burn rapidly in the combustion chamber, which plays a important role in improving the efficiency of micro combustor. The wall material of micro combustor is made of selective radiation material (MgO ceramic) [15], and the kind of material can improve the utilization of radiation energy and thus improve the total efficiency of system, combining with corresponding PV elements [15]. The said corresponding PV element involves the one whose maximum absorption wavelength range λ is consistent with maximum emission wavelength range of micro combustor.

In the research field of photovoltaic materials, JX Crystals Company of America develops a kind of photovoltaic cell with the material of GaSb (gallium-stibium alloy), and the energy band gap is 0.72eV [15]. Figure 4 shows the distribution of conversion efficiency of GaSb material along wavelength [15]. From the figure, it is known that as long as most of wavelength of photons radiated by micro combustor concentrates in the range of $0.9 \le \lambda \le 1.6\mu m$, the photon absorption efficiency in the range by photovoltaic cell can be up to about 90%.

Figure 5 shows the spectral radiation property of MgO ceramic combustor [16]. In the figure, when the temperature is up to 1404℃, the corresponding peak wavelength $\lambda_{max}=0.9\mu m$, and the radiation energy is largest. According to the technical levels of current selective filter layer and photovoltaic cell, the best operational temperature for radiator of MTPV system is about 1200K [3,9]. Based on the Wien thermodynamics theory, the maximum spectral radiation force will increase quickly and the corresponding peak wavelength will move towards short wave gradually as the temperature T increases. MgO ceramic used in the test is a kind of selective radiation material that is mixed with certain a proportion of NiO or CoO and manufactured with the tap casting process. At the temperature of 1000-600K, the radiation wavelength concentrates in the visible light of $\lambda \le 1.7\mu m$ and near infrared wavelength, and the radiation energy of other wavelengths is less. Namely, when the wall temperature of MgO ceramic combustor is at 1200-600K, the best conversion efficiency of photovoltaic cell can be reached, and in the range the higher the temperature is, the larger the radiation energy is.

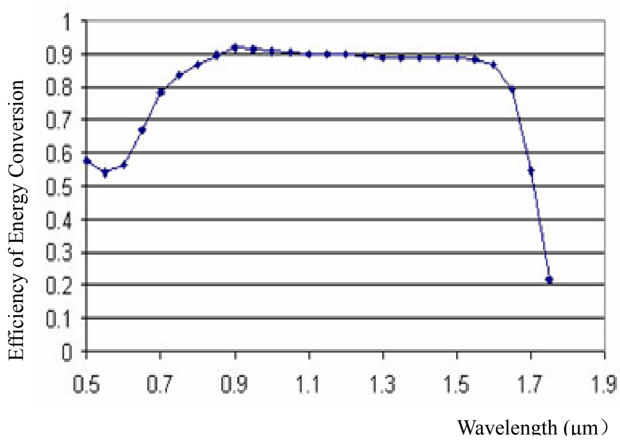


Figure 4 Distribution of Conversion Efficiency of GaSb Material along Wavelength

In a word, according to the analysis in the test above, when other external conditions are kept constant and the temperature of external wall of micro combustor is increased as possible, the micro combustor will get better performance as long as the temperature distribution of external wall of micro combustor is higher and more uniform. In this paper, through the comparison of temperature distributions of tubular micro combustor when the factors including inlet flow, porosity, mixture ratio of CH_4/O_2 and wall thickness of micro combustor are changed, the best parameter is selected for the MTPV system combustor.

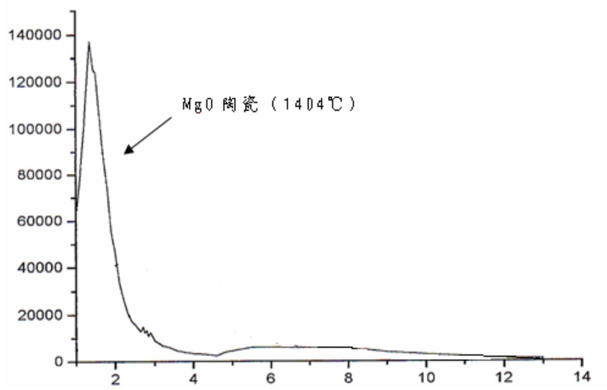


Figure 5 Spectral Radiation of Selective MgO Radiator

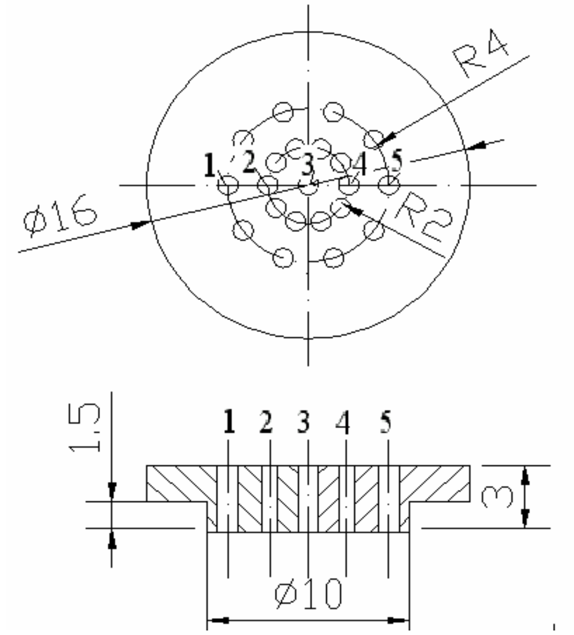
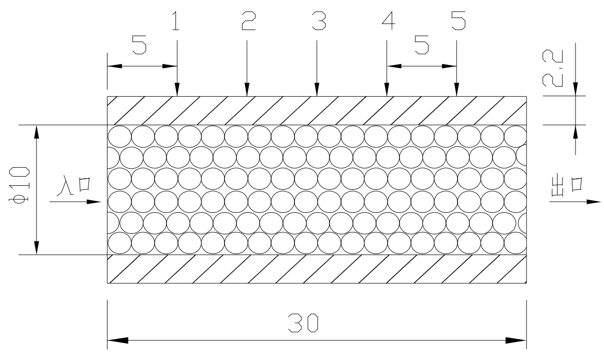


Figure 6 Schematic of Experimental Measuring Locations of External Wall Surface and Outlet End Surface of Combustor

4. Research on Experimental Process of Combustor and Scheme

5 temperature-measuring points are set successively and uniformly on the walls of two kinds of micro combustors respectively along the diameter and center line at the outlet, shown in Figure 6 below. Then the temperature change of each point is observed and the changing rule of external wall temperature of micro combustor is summarized when all the factors including inlet flow, porosity, mixture ratio of CH_4/O_2 and wall thickness of micro combustor are kept constant.

Temperatures are measured with S-type rhodium-platinum thermocouple with the diameter of 0.3mm.



4.1 Influence of porosity *ε* on combustor performance

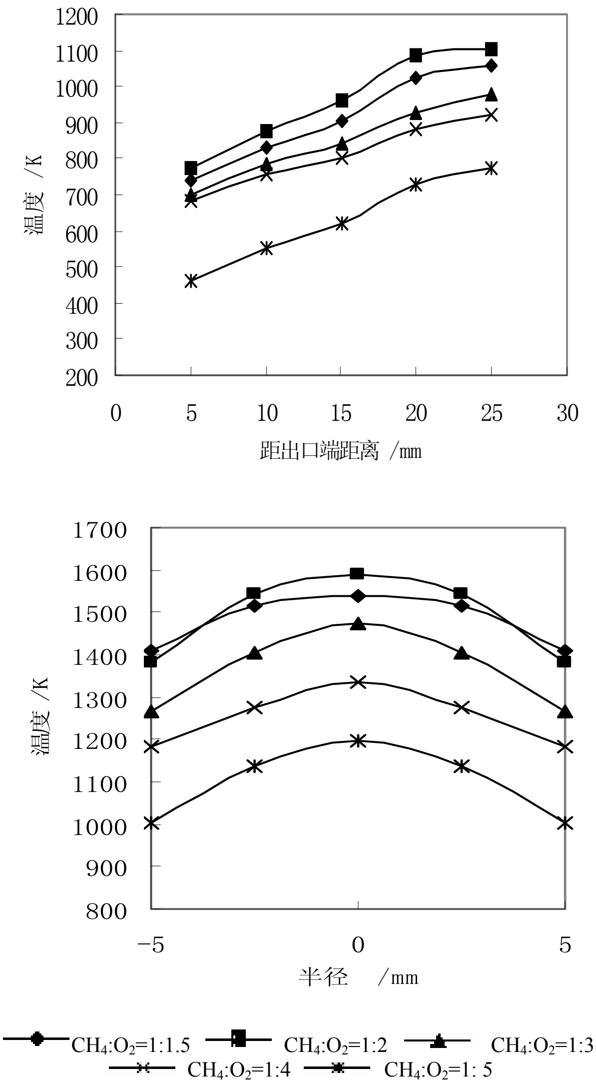
4.1.1 Experiment of tubular combustor

Experimental phenomena: (1) flame ejects out of the tube (the flame is longest when the volumetric mixture ratio of $CH_4:O_2=1:1.5$), and the flame will withdraw into the tube slowly as the flow decreases or the excess-air coefficient increases. (2) When the volumetric mixture ratio of $CH_4:O_2=1:2$, the temperature of tubular wall is highest; the tubular wall shows dark red; the noise is lowest; the maximum temperature is up to about 1100K, and the high temperature zone is distributed near the outlet but not enough wide, as shown in the experimental photo of Figure 7. (3) There are small amount of carbon black at the orifice of tube. (4) The flameout limit appears when the volumetric mixture ratio of CH_4/O_2 is 1:5, and the excess-air coefficient during stable combustion has a narrow range. Figure 8 shows the temperature distribution when the flow of tubular combustor is 105ml/min and the mixture ratio is varied.

4.1.2 Experiment of Porous Medium Combustor

Porosity *ε* is the ratio of void volume *Vv* in the porous medium to total volume of porous medium *Vt*, and

Figure 7 Combustion Phenomena of General Combustor



(a) Temperature of wall surface (b) Temperature of outlet

Figure 8 Distribution of Wall Temperature of Tubular Combustor

also one of important parameters influencing the combusting heat transfer in the porous medium. According to different diameters of ceramic balls filled in the combustion tube, the forming porous structures are different in porosity. In the experimental research of this paper, the combustion tubes with the porosities of respectively 0.37, 0.42 and 0.68 and the tube without ceramic ball filled (ε=1) are adopted.

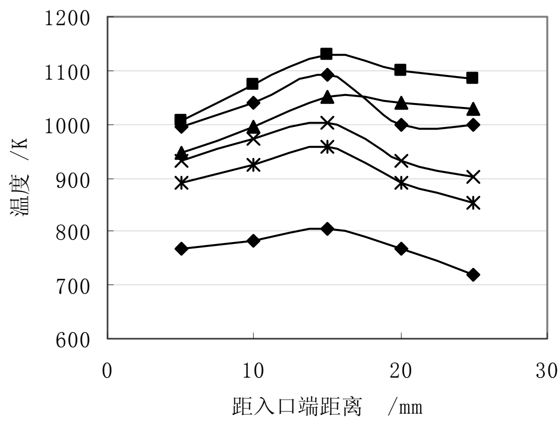
Experimental phenomena: (1) it is difficult to ignite, and the gas inside the tube will be burnt only when the temperature at Point 1 basically reaches about 200℃. (2) The flame will run out of tube only when the methane is excessive. The flame withdraws into the tube slowly as the oxygen proportion increases. (3) When the volumetric mixture ratio of CH_4:O_2=1:2, the temperature of tubular wall is highest, the noise is lowest, and dazzling light is produced. The light is more dazzling as the flow increases. As the excess-air coefficient increases, the light of tubular wall varies from dazzling, yellow white, red to dark red, and then disappears slowly. (4) No carbon black is produced at the orifice of tube. (5) The flame will extinguish when the volumetric mixture ratio of CH_4:O_2=1:9 approximately. Figure 9 shows the experimental picture of porous medium combustor when the inlet flow is 150ml/min and the volumetric mixture ratio of CH_4/O_2 is 1:2.

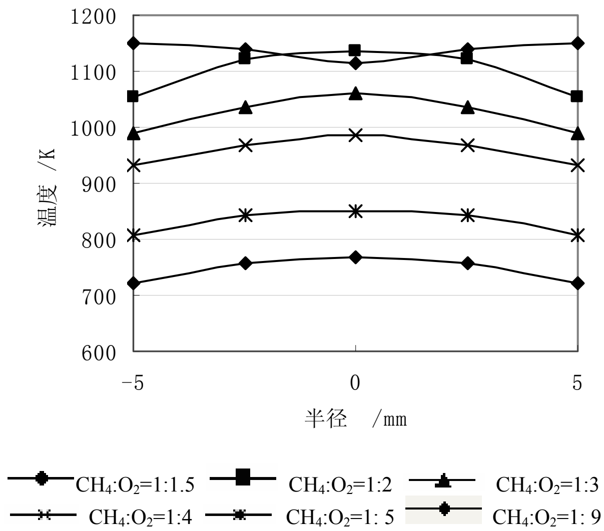
Figure 9 Experiment of Porous Medium Combustor

Figure 10 shows the temperature distribution curve of porous medium combustor when the inlet flow is 105ml/min and the working conditions of different volumetric mixture ratio of gas are provided.

As shown in Figure 10a, when the volumetric mixture ratio of CH_4:O_2=1:2, the temperature of wall surface is highest; the temperature of wall surface decreases successively as the excess-air coefficient increases; the high temperature zone has a uniform distribution. As shown in Figure 10b, when the volumetric mixture ratios of CH_4:O_2=1:2, 1:3, 1:4, 1:5 and 1:9 respectively, the temperature in the middle of outlet is highest; when the volumetric mixture ratio of CH_4:O_2=1:1.5, the flame will run out of tube, and the temperature of middle measuring location is lower because it is in the area of inner flame; compared by tubular combustor, the outlet temperature decreases obviously and tends to be uniform, and the thermal loss is reduced, facilitating the improvement of thermal utilization of combustor.

From the experimental results above, the porous medium combustor is ideal in respects of temperature





(a) Temperature of wall surface (b) Temperature of outlet

Figure 10 Temperature Distribution of Porous Medium Combustor (Porosity ε=0.37)

distribution of tubular wall as well as the consumption and effective utilization of fuel.

Table 1 shows the average temperature of wall surface of combustor obtained experimentally under the conditions of different porosity, different inlet flow Q and chemical equivalence ratio of mixed gas α=1 (arithmetic mean of 5 temperature-measuring points on the wall of combustor is the average temperature of wall surface).

Table 1: Average Temperature of Wall Surface of Each Combustor in Different Flows (equivalence ratio of CH_4/O_2 α=1)

Combustor		Flow Q/(cm^3/min)			
Porosity	Area-volume ratio Ω/m^{-1}	50	75	105	150
1.00	0.48	803.3	899.4	974.6	1022.7
0.68	768	/	944.5	1036.0	1153.2
0.42	835	855.4	991.8	1070.2	1117.6
0.37	1120	833.7	962.3	1026.0	/

From Table 1, the average temperatures of wall surface of porous medium combustor are above 1000K when the inlet flow Q=105 cm^3/min, while the average temperature of wall surface of tubular combustor is up to 1000K only when Q=105 cm^3/min. It is indicated that porous medium structure can get a higher fuel utilization.

Figure 11 shows the influence of different porosities on wall temperature and outlet temperature of combustor. From Figure (a), when the porosity is equal to 1 (tube), the wall temperature of combustor increases gradually from inlet to outlet, with a larger variation amplitude. It is shown that because the gas resides in the tube in a short time, the combusting heating produced by mixed gas is less at the beginning of combustion, and the main

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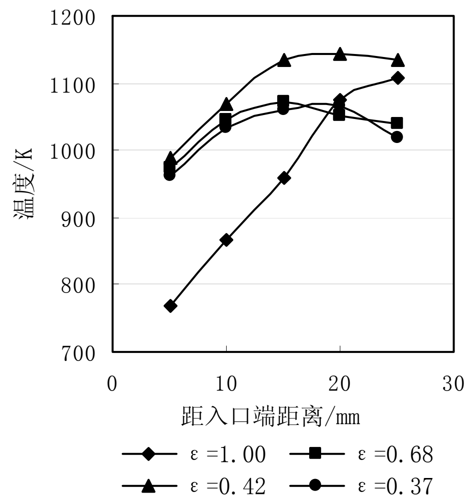
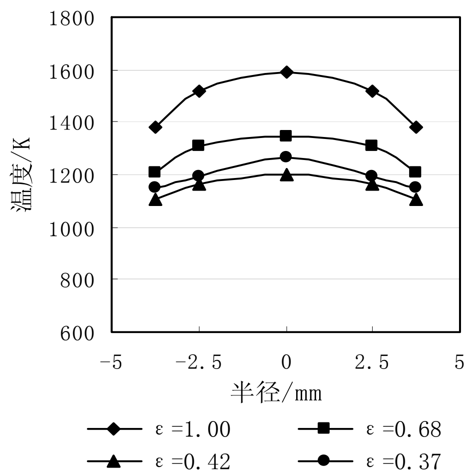
combusting heat concentrates at the end of combustor. When the porous medium structure is adopted, mixed gas can flow and burn in the voids. The gas is effectively heated by the solid framework of porous medium so as to completely burn. The wall temperature of porous medium combustor is evidently greater than that of tubular combustor. But from Figure (b), the outlet temperature of tubular combustor is higher. It is indicated that the combusting loss increases.





(a)Temperature of wall surface (b) Temperature of outlet

Figure 11 Influence of Porosity ε (Q=105cm^3/min, α=1)

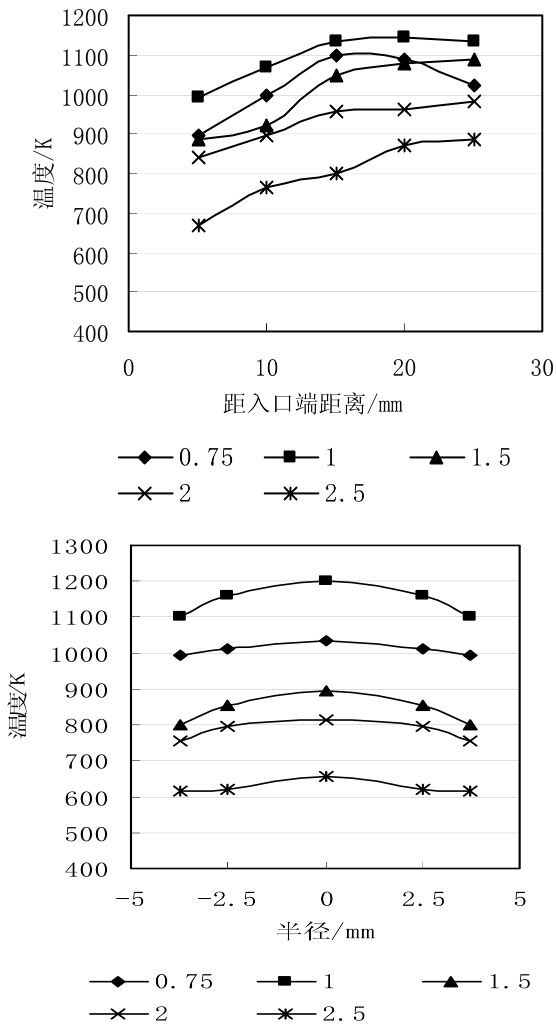
From the experimental results, after the porous medium is adopted, the wall temperature of combustor increases gradually from inlet to outlet and the combustion products in the voids increase as the combusting heat increases, which influences the later combusting heat and causes the wall temperature of combustor to decrease to some extent. The wall temperature of combustor shows a change of early ascent and later descent. With the decrease of porosity, the location of maximum wall temperature moves towards the inlet section. It is indicated that when the porosity is smaller, the existence of combustion products aggravates the combustion influence on fuels not combusted.

Experimental results show that, when the porosity decreases to 0.42 from 0.68, the wall temperature of combustor increases and the gradient of wall temperature distribution decreases; at the same time, the outlet temperature decreases. When the porosity decreases to 0.37, however, the wall temperature of combustor decreases to some extent and the outlet temperature increases to some extent. This is because the area-volume ratio Ω (the ratio of total surface area A of solid framework to total volume V of porous medium) increases when the porosity decreases to some extent. Although the fuel is heated effectively by the solid framework and gets complete combustion, the combustion stability will be influenced by appropriately increased heat dissipation area because of increased area-volume ratio; meanwhile, the combustion space is very small, which reduces the residence time of fuels and causes incomplete combustion and heat exchange.

4-2 Influence of Mixture Ratio of CH_4/O_2 on Combustor Performance

The process of combustion reaction depends on the density, temperature and residence time in high temperature zone of fuel, and thus the mixture ratio of CH_4/O_2 is a key factor influencing the combustion process in the porous medium.

Figure 12 shows the experimental results of external wall temperature and outlet temperature of combustor influenced by the equivalence ratio α of CH_4/O_2 when the porosity is 0.42 and the mixed gas flow Q =105 cm^3/min. From the figure, when the porosity and mixed gas flow are kept constant, the temperatures of external wall and outlet of combustor will change correspondingly with the change of mixture ratio of CH_4/O_2. According to the reaction equation, when completely combusting, the mixture ratio of mixed CH_4/O_2 gas is 1:2. Therefore, when the mixture ratio of CH_4/O_2 is about 1:2 (namely the equivalence ratio α=1), the wall temperature and outlet temperature of combustor are higher; however, with the decrease or increase of CH_4 proportion in mixed gas, thermocouples show that both of external wall temperature and outlet temperature decrease remarkably. This is because incomplete combustion is aggravated when the density of CH_4 is excessive; when CH_4 is too thin, lower thermal value is produced by less CH_4 although the fuel is completely burnt. In the two cases, The excessive gases will absorb some thermal energy (Co_2=5R/2).



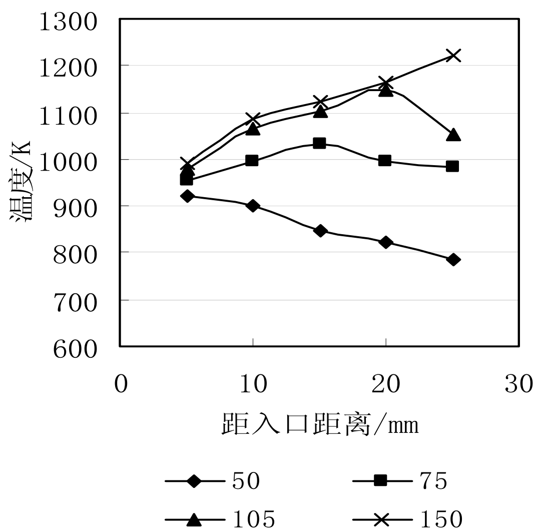
(a) Temperature of wall surface (b) Temperature of outlet

Figure 12 Influence of Mixture Ratio α of CH_4/O_2 (α=4.2, mixed gas flow Q=105cm^3/min)

Therefore, in order to obtain the combustion temperature required for thermophotovoltaic conversion, the mixed gas will be completely burnt and the mixture ratio of CH_4/O_2 should be kept to be about 1:2.

4-3 Influence of Inlet Flow of Mixed Gas on Combustor Performance

Figure 13 shows the experimental results of wall temperature and outlet temperature of combustor influenced by the inlet flow Q when the porosity is 0.42 and equivalence ratio of mixed CH_4/O_2 gas α is 1. From Figure 13, when the porosity and mixture ratio of CH_4/O_2 are kept constant, the wall temperature and outlet temperature will increase correspondingly with the increase of inlet flow Q. To make the wall temperature of combustor reach some temperature, enough inlet flow Q must be ensured. However, the inlet flow should not be excessive. From the condition of Q =150 cm^3/min, the wall temperature does not get an obvious increase, while the outlet temperature rises evidently and the thermal loss increases. This is because the increased flow quickens the flow speed, reduces the residence time of gas, makes the gas in the tube burn incompletely and decreases the fuel utilization. Although the tubular wall temperature increases, the combustion efficiency decreases, thus reducing the comprehensive thermal efficiency.



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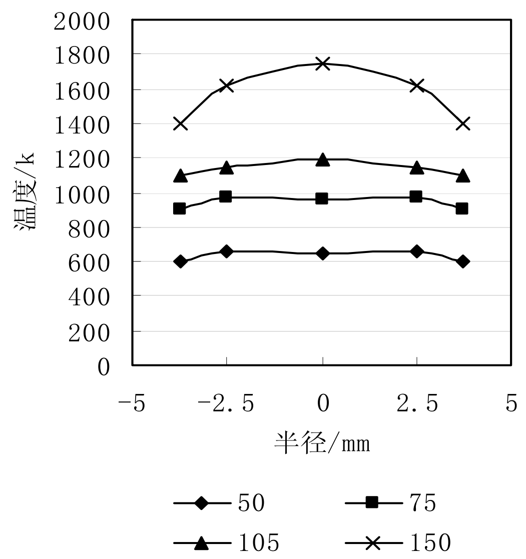


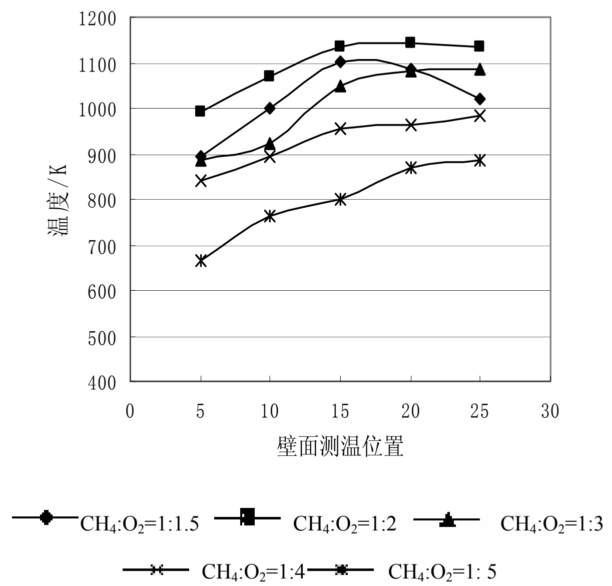
(a) Temperature of wall surface (b) Temperature of outlet

Figure 13 Influence of Inlet Flow Q (cm^3/min) (α=1, ε=0.42)

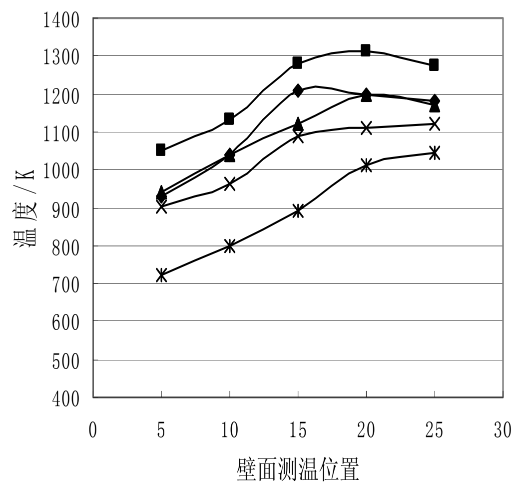
When the porosity is 0.42 and the equivalence ratio of mixed CH_4/O_2 gas *α* is 1, the highest external wall temperature will not be obtained by adopting the inlet flow of *Q* =105 cm^3/min, but the better combustion efficiency can be obtained. From the figure above, when *Q* =105 cm^3/min and *Q* =150 cm^3/min, the temperatures at previous 4 temperature-measuring points are very close to each other. Only the last measuring point shows a larger difference, and the difference tends to be greater. It is indicated the combustion of fuel will move towards the rear section obviously as the flow increases, and the flow speed accelerates and the residence time of fuel in the tube becomes short. This is verified by the temperature-measuring points at the outlet, and when *Q* =150 cm^3/min, the maximum outlet temperature will be 400K greater than the temperature when *Q* =105 cm^3/min. Therefore, selection of *Q* =105 cm^3/min maximizes the improvement of fuel combustion efficiency on the condition that the external wall temperature of combustor is not reduced basically.

4-4 Influence of Wall Thickness on Combustor Performance

Ceramic tube combustor with the inside diameter of d=10mm and the length of L=30mm is adopted in the experiment, and the experiment is performed at the wall thickness of respectively 2mm and 3mm to measure the distribution of wall temperature under different conditions. Figure 14 shows the experimental results of wall temperature and outlet temperature of combustor influenced by different volume mixing ratio when the porosity is 0.42 and the inlet flow Q is 105ml/min. From Figure 13, when the porosity and mixture ratio of CH_4/O_2 are kept constant, the wall temperature and outlet temperature will increase correspondingly with the increase of inlet flow *Q*.

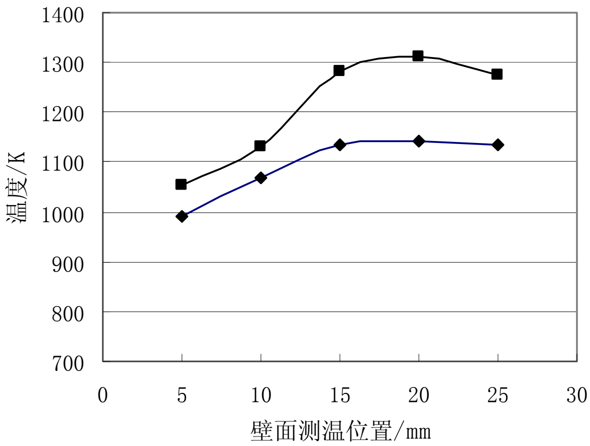


（a）3mm 壁厚的壁面温度



—◆— CH_4:O_2=1:1.5 —■— CH_4:O_2=1:2 —▲— CH_4:O_2=1:3
—✕— CH_4:O_2=1:4 —✱— CH_4:O_2=1: 5

（b）2mm 壁厚的壁面温度



(c) —■— Temperature of 2mm Wall Thickness —◆— Temperature of 3mm Wall Thickness（Q=105cm^3/min、ε =0.42、CH_4:O_2=1:2）

Figure 14 Distribution of Wall Temperature of Combustor

From the figure, when the porosity and mixed gas flow are kept constant, the wall temperatures of combustor changes with the change of mixture ratio of CH_4/O_2. According to the chemical reaction equation, when completely combusting, the mixture ratio of mixed CH_4/O_2 gas is 1:2. Therefore, when the mixture ratio of CH_4/O_2 is about 1:2 (namely the equivalence ratio is 1), the wall temperature of combustor is highest, while the wall temperature will decrease with the reduction of fuel in the mixed gas. Thus, in order to obtain the combustion temperature required for thermophotovoltaic conversion, the mixture ratio of CH_4/O_2 should be kept to about 1:2. From the temperature distributions of these two combustors, the maximum wall temperature of combustor with wall thickness of 2mm can be up to 1300K when the mixture ratio is 1:2. From the average temperature of tubular wall, the average wall temperature of combustor with the wall thickness of 2mm is approximately 100K greater than that of combustor with the wall thickness of 3mm. It is indicated the thick wall retards outward thermal energy transmission, and thus the combustor with thinner wall should be selected. However, only the combustors with the wall thicknesses of 2mm and 3mm are tested because of the limitation of machining and manufacturing techniques.

With the further decrease of wall thickness, however, some unexpected problems appear:

(1) Ceramic tube combustor is very easy to explode. The increase of temperature and the decrease of wall thickness pose a great challenge to the reliability of structure.

(2) Thermal loss increases. Assume that when environmental temperature is constant, too small wall thickness will cause excessive temperature gradient between two sides of wall, and however, thermal loss will increase with the decrease of wall thickness.

(3) The cost of machining and manufacturing techniques increases. With the further decrease of wall thickness, the machining of MgO combustor is more difficult, and general machining technique is hard to meet the requirement for smaller wall thickness.

5. Results of Research and Prospect

Through the experimental research above, it is our understanding that when ε=0.42, the mixture ratio of mixed CH_4/O_2 gas is 1:2, Q =105 cm^3/min, and the wall thickness is 3mm, the external wall of combustor can get a higher temperature and the combustion efficiency of fuel is highest in this time.

However, the future development direction for MTPV system is: (1) miniaturization, (2) high efficiency. With the further decrease of combustor size, the porous medium structure will not be applicable. This is because the area-volume ratio relatively increases, correspondingly augmenting the heat dissipation area; the combustion space decreases, reducing the residence time of fuel and causing incomplete combustion and heat exchange, and finally extinguishment. Different sizes of micro combustor directly influence different best flow, best mixture ratio and most proper wall thickness of the combustor. In the field of miniaturization, attempts have been made for flatbed combustor with d=0.2mm ap-

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proximately by University of Jiangsu, and some achievements have been obtained. Our research mainly focuses on the range of several millimeters, and improves the combustion and emission efficiency as possible. In a word, according to different micro mechatronic systems, the energy systems with different sizes will be widely used.

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