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Development of an Engineering–Model of Hydrogen-Fueled Ultra-micro Combustor for UMGT

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Abstract

To develop an engineering-model of hydrogen-fueled ultra-micro combustor for Ultra Micro Gas Turbine (UMGT), we reviewed and summarized the problems in downsizing combustors, and determined a suitable burning method. The key issue to actualize practical ultra-micro combustors is reducing heat loss from the combustor to compressor and turbine. The reduction of heat loss was discussed from 3 different viewpoints; heat-insulation material, high-space-heating-rate combustion, and combustor-insolated gas turbine structure. Use of heat-insulation material induced the heat loss reduction to the surroundings. The heat loss ratio decreased substantially in reverse proportion to space heating rate, leading the idea that it could be reduced by burning at a high space heating rate. By settling the combustor insolated from the compressor and turbine, the heat transfer from the combustor to the compressor and turbine becomes smaller. For a selection of the suitable burning method, comparison between 2 burning methods, flat-flame and swirling-flamer types, was conducted. Synthetically the flat-flame burning method was confirmed to be more suitable for ultra-micro combustors than latter one. Base on them, an engineering-model of hydrogen-fueled flat-flame ultra-micro combustor was developed. To obtain high overall heat-insulation, heat-resistant and strength, the engineering-model combustor had triple layer structure with an advanced ceramic, a heat insulation material and a stainless steel. To simplify heat transfer issue in the combustor, it was isolated from the other components. Furthermore it was designed by considering structure, size, material, velocity, pressure loss and prevention of flashback.

Introduction

The dime sized Ultra-micro Gas Turbine (UMGT) shown in Fig.1 was proposed by MIT in 1995[1]. Although this state-of-art device has gathered many attentions for more than 10 years, it is the status quo that no single UMGT has been actualized yet. To actualize UMGT with an output of 10 to 100 W, technological break-throughs are needed for each element. Turning to ultra-micro combustor, one of the essential components for UMGT, it should be smaller and lighter obviously, and keep high flame stability and combustion efficiency.

Thermal issues and micro-flame characteristics among development of ultra-micro combustors in the order of mm are getting clear[1, 2, 3]. Based on consideration of combustion problems, we developed prototype-model hydrogen-fueled ultra-micro combustors and examined experimentally[3–6]. These studies declared that fruition of high-space-heating-rate combustion was the most important key technology for practical ultra-micro combustors [7].

Here our investigation is moving onto development in an engineering-model of hydrogen-fueled ultra-micro combustor. Before discussing concept of that, we would recall and summarize issues in downsizing combustors, especially from the standpoints of influence of space heating rate for combustors and suitable burning method. The objectives of this paper are to review issues in the development of ultra-micro combustors briefly, and, based on them, to design an engineering-model of hydrogen-fueled ultra-micro combustor.

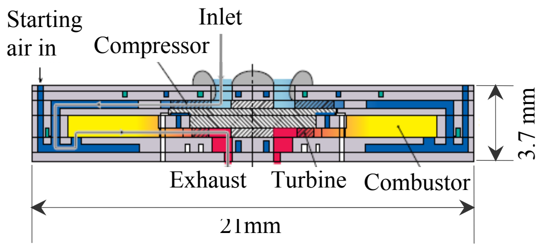


Fig.1 MIT first UMGT concept [1]

Specified Issues

A. Problems Related to Downsizing Combustors[3]

As the first discussion about ultra-micro combustor, we should point out following peculiar problems in ultra-micro-scale combustion; relative increase in quenching distance, higher heat loss ratio, shortened diffusion characteristic time of mass, and flow laminarization. In order to downsize a combustor, the characteristic problems, which are mostly ignored in conventional gas turbine combustors, must be taken into account. These factors are assumed to cause substantial influence for whole flame zone in the tiny space.

a. Relative Increase in Quenching Distance

For instance, quenching distance of hydrogen/air premixture of stoichiometric ratio is about 0.64mm known as the measurement value[8], while the height of UMGT in MIT first concept is designed about 3mm. The effect of quenching distance relatively increases along downsizing combustors. Something else to be borne in mind here is that hot combustion chamber wall doesn't leads the same effect[9].

b. Higher Heat Loss Ratio

Heat loss ratio HLR is defined as $HLR \equiv HL/Q \sim \ell^2/\ell^3 = 1/\ell$, which indicates the heat loss ratio is in inverse proportion to combustion scale. Therefore in a downsized combustor, neither the decrease of chemical reaction rate caused by temperature decrease in flame zone nor the heat losses to wall and rim is ignorable.

Beyond that, the heat loss issues should be considered not only as absolute combustion problem, but also in influence for the whole system of UMGT. The system structure must enable to avoid performance reduction by heat transfer to the compressor and turbine[3].

c. Shortened Diffusion Characteristic Time of Mass and Heat

The diffusion characteristic time represented as ℓ^2/D is shortened by downsizing combustors. The biggest influence from this problem is rapid uniformity of density distributions. At same time, the Damköhler number defined as $Da \equiv \tau_{res}/\tau_{chem}$ becomes smaller, that induces expanding of diffusion flame zone or blowing off. As a note, it is found that residence time can be evaluated with space heating rate[7].

d. Flow laminarization

The main parameter that determines flow condition is the Reynolds number defined as $Re \equiv U_c \cdot \ell/\nu$. In an ultra-micro combustor, extremely shortened ℓ and increased ν as temperature increases make the Reynolds number small, obviously. Inevitably, the flow in the ultra-micro combustor is laminarized.

B. Prerequisite Conditions of Ultra-micro Combustors for UMGT[6]

In order to downsize a combustor for UMGT, the following characteristic factors must be achieved in addition to the fundamentally important scaling factors for ultra-micro combustor described in the previous section[5]; low pressure loss, low heat loss, high space heating rate, and premixed combustion.

a. Low Pressure Loss

Generally for micro gas turbines, a pressure loss must be in the range of 3 to 5%. Hence combustors which have long paths or high pressure ratio involved by high velocity in the chambers, the Swiss-roll combustor as an example, are unfavorite for UMGT, in spite of good flame stability or thermal characteristics.

b. Low Heat Loss to the Surroundings

Reduction of the heat transfer from the chamber to the other components, inducing the thermal efficiency decline, should be the most important and difficult issues in developing a practical ultra-micro combustor for UMGT. What was demonstrated in the previous examination is that use of insulation material could greatly reduce heat loss from combustor[9]. However, no material satisfies enough strength, heat-resistant and heat-insulation with achieving small and light UMGT, as far as we know. Instead, other strategies to the reduce heat loss should be suggested. One is considered from the combustion theoretical side. It was clarified that heat loss ratio could be decreased by high-space-heating-rate combustion[7]. Another is from the standpoint of gas turbine structures. As to combustors bounded by compressor and turbine, for example MIT first UMGT concept in Fig.1[1], it is quite difficult to reduce the heat transfer from the combustor to the other components. For this reason, at the state of affairs, it is reasonable to suppose that the combustor is settled down separately from the compressor and turbine.

c. High Space Heating Rate

As downsizing gas turbine combustors, ratio of combustion chamber volume to air mass flow rate decreases. Necessarily space heating rate must be higher. In addition, it is found that residence time and heat loss ratio, the important factors in downsizing combustors, are improved by high-space-heating-rate combustion[7]. We would like to discuss this topic a little more fully, later.

d. Premixed Combustion

In ultra-micro combustors, laminar flow prevents rapid mixing between fuel and air, and when using a micro fuel injector, fuel diffuses to the surroundings before reaching the flame base. These phenomena suggest that premixed combustion, instead of diffusion combustion, should be selected in ultra-micro combustors.

C. A Possible Solution with Flat-flame Burning Method

The development of ultra-micro combustor for UMGT requires burning method satisfying those 4 prerequisite conditions. To this purpose, we proposed flat-flame burning method[4,5]. The mechanism of fat-flame burning method balances the burning velocity that is higher than premixture velocity with premixture velocity by reducing the burning velocity with heat conduction losses to the flame holder[9]. The flat-flame burning method was confirmed its suitability for the ultra-micro combustor[6,7]. The flat-flame combustor achieves premixed combustion with low pressure loss, and other 2 requirements, heat loss reduction and high space heating rate, remain as combustion issues.

Influences of Space Heating Rate upon Combustor Performance

A. Theoretical Approach

a. Relationship between Space Heating Rate and Heat Loss Ratio[7, 10)]

SHR is generally determined as

$$SHR \equiv \frac{\dot{m}_f \cdot \Delta H}{V_c \cdot P_c} \sim \frac{\dot{m}_f \cdot \Delta H}{\ell^3 \cdot P_c} \quad (1)$$

We defined the heat loss ratio *HLR* as following;

$$HLR \equiv \frac{HL}{Q} \quad (2)$$

Since *HL* and *Q* are represented as

$$HL \equiv HT \cdot S \cdot \Delta T \sim HT \cdot \ell^2 \cdot \Delta T \quad (3)$$

$$Q \equiv \dot{m}_f \cdot \Delta H \sim SHR \cdot \ell^3 \cdot P_c \quad (4)$$

HLR is given with *SHR* as

$$HLR \equiv \frac{HL}{Q} \sim \frac{HT \cdot \Delta T}{SHR \cdot \ell \cdot P_c} \quad (5)$$

If ΔT is given as a function of *SHR,*

$$\Delta T \cong f(SHR) = \alpha \cdot SHR^{\beta} \quad (6)$$

because the temperature of combustor outer wall should increase as *SHR* increases. If *HT* and P_c are constant, *HLR* is simplified as

$$HLR \sim \frac{\alpha \cdot SHR^{\beta}}{SHR \cdot \ell} \sim \frac{SHR^{\beta-1}}{\ell} \quad (7)$$

This relation indicates that *HLR* increases as the size of the combustor decreases, but that this value can be reduced by increasing *SHR*.

Additionally, *SHR* can be simplified as

$$SHR \sim \frac{\varphi \cdot \dot{m}_a}{V_c \cdot P_c} \sim \frac{\varphi \cdot S \cdot v}{V_c} \sim \frac{\varphi \cdot v}{\ell} \quad (8)$$

Hence, when assuming complete combustion, *HLR* reduction is expected by increase of air mass flow rate at constant equivalence ratio in the same combustor, and by combustion in smaller volume[10)].

b. Relationship between Space Heating Rate and Residence Time[3, 6, 7, 10)]

Using following equations,

$$\dot{m} = \rho \cdot S \cdot v \quad (9)$$

$$\dot{m}_f = ST \cdot \varphi \cdot \dot{m}_a \cong ST \cdot \varphi \cdot \dot{m} \quad (10)$$

$$P_c \sim \rho \quad (11)$$

$$V_c \cong S \cdot \ell \quad (12)$$

SHR can be represented with τ_{res} as

$$SHR \sim \frac{ST \cdot \varphi \cdot \dot{m} \cdot \Delta H}{V_c \cdot P_c} \sim \frac{ST \cdot \varphi \cdot \Delta H \cdot S \cdot v}{V_c} \sim \frac{ST \cdot \varphi \cdot \Delta H \cdot v}{\ell} \cong \frac{ST \cdot \varphi \cdot \Delta H}{\tau_{res}} \quad (13)$$

This shows that τ_{res} depends on only *SHR* without any relationship on the downsizing, when heat release in the combustion chamber per unit air mass flow rate, $ST \cdot \varphi \cdot \Delta H$, is at same grade. In fact, that is made clear in the graph of relationship between *SHR* and τ_{res} about some gas turbine combustors in Fig.2. This illustrates that the lower *SHR* is, the longer τ_{res} is.

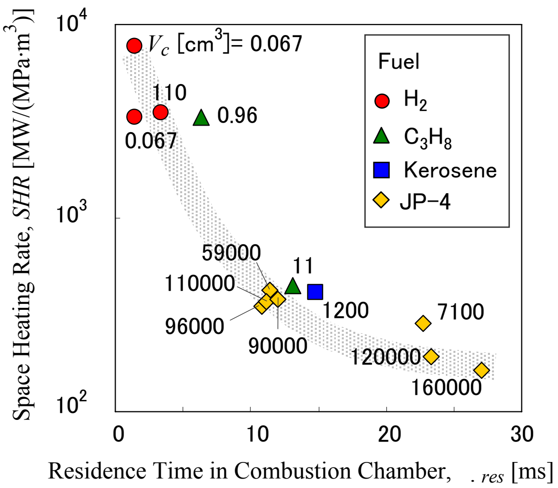
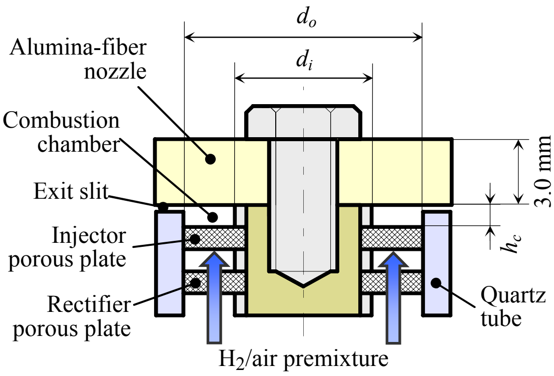


Fig.2 Residence time τ_{res} samples of engines and combustors

B. Experimental Examination with Prototype-Model Flat-flame Ultra-micro Combustors

a. Prototype-Model Flat-flame Ultra-micro Combustors

Figure 3 (a) and (b) show a schematic of a prototype-model flat-flame combustor and the appearance of hydrogen-fueled flat-flame. The original-sized flat-flame combustor with a diameter of 10.5mm and a chamber height of 1 mm is represented as $\phi 10h1$, and the double-sized combustors with diameters of 18.5mm and a chamber height of 1 or 2mm are represented as $\phi 20h1$ and $\phi 20h2$, respectively. The detail of the combustors and experimental procedure were described in our previous paper[5,6,9)]. The experiment was conducted with hydrogen as a fuel and at constant equivalence ratio of φ=0.4, room temperature and atmospheric pressure.



	Original size	Double size	
	φ10*h*1	φ20*h*1	φ20*h*2
d_o -d_i -h_c [mm]	10.5-5-1	18.5-6-1	18.5-6-2
V_c [mm^3]	67	241	481
W_c [W]	16	50	
$\dot{m}_a$ [g/s]	0.037	0.15	

Fig.3(a) Schematic of prototype-model flat-flame ultra-micro combustors

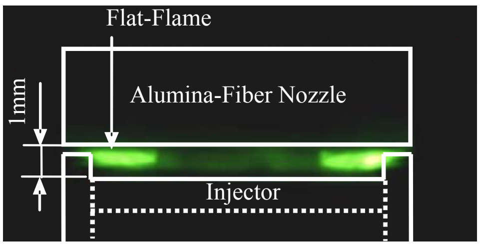


Fig.3(b) Image intensifier photograph of hydrogen/air flat-flame in the $\phi 10h1$ original-sized combustor (exposure time: 1/30[s], φ=0.4, $\dot{m}_a$ =0.037[g/s])

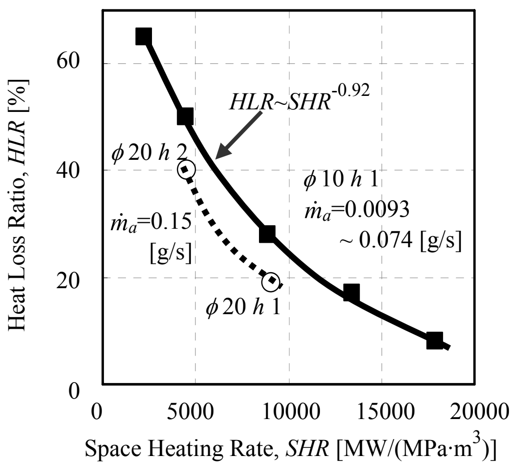


Fig.4 Relationship between Space Heating Rate *SHR* and Heat Loss Ratio *HLR* (=0.4) [7]

b. Result: Space Heating Rate-Heat Loss Ratio

Figure 4 show the relationship between *SHR* and *HLR* obtained for various *SHR* by varying the air mass flow rate or the sizes of combustors[7]. Here *HLR* were evaluated by the following equation

$$HLR = \frac{H_{in} - H_{ex}}{Q} = 1 - \frac{\left(\dot{m}_a + \dot{m}_f\right)\cdot C_p \cdot \left(T_{ex} - T_{in}\right)}{Q} \qquad (13)$$

The result suggested that, *HLR* was decreased as *SHR* was increased. Using the same combustor, *HLR* could be reduced by burning at a high *SHR*. Under the constant condition of *SHR*, the comparisons among three combustors, having different sizes, confirmed that the larger combustors had lower *HLR* than the smaller one[7]

c. Result: Space Heating Rate-Residence Time

Figure 5 plots the relation between *SHR* and τ_{res} in the combustor chambers at the stability limits for all combustors[7]. This result showed the relationship of $SHR\cdot\tau_{res} \cong$ constant. That confirmed τ_{res} depended on not the combustor size but *SHR*, as far as combustion completes inside of the combustion chambers[7].

Consequently, to take relationship between heat loss rate and space heating rate into account, the realization of high-space-heating-rate combustion is the most challenging requirement among the prerequisites for UMGT[6].

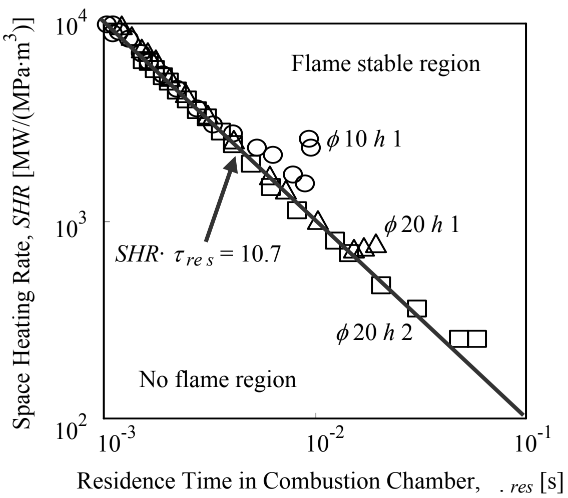


Fig.5 Relationship between Space Heating Rate *SHR* and residence time τ_{res} [7]

Appropriateness of Flat-flame Burning Method for Ultra-micro Combustor

To accomplish high flame stability and combustion efficiency in ultra-micro combustors, we proposed flat-flame burning method. Evidence that this burning method is suitable for ultra-micro combustors can be seen in comparison with swirling-flame burning method, commonly used for conventional micro gas turbine combustors. It was already confirmed that in both our flat-flame and swirling-flame type combustors, the stable flame regions sufficiently satisfied around their operation points and the combustion efficiencies exceeded 99.5% at φ>0.4 [6,7].

Here, we would like to remind comparison of 2 burning methods by the points of 4 prerequisite conditions for the ultra-micro combustors mentioned before. First of all, pressure losses at combustors were quite different because of their injector structure[11]. That needs explanation later. Second, the heat loss ratio couldn't compare accurately, since both of prototype-model combustors were designed with different structures and materials. Third, in both combustors, high space heating rates were confirmed; 7100MW/(m^3·MPa) at the $\phi10h1$ original-sized flat-flame combustor and 7200MW/(m^3·MPa) at the swirling-flame combustor at design point[11]. Forth, both combustors adopted premixed combustion.

A. An Prototype-Model Swirling-flame Ultra-micro Combustor for Comparison with the Flat-flame Combustor

Figure 6 (a) and (b) show schematic of a swirling-flame combustor and appearances of swirling-flames. The detail of combustor and experimental procedure were described in our previous paper[6,7,11]. According to the previous papers, the swirling-flame combustor has completely different flame stabilizing mechanism from the flat-flame one. Near the design point, 4 Bunsen-type flames attached on infector exits with narrow rims. As the equivalence ratio decrease keeping air mass flow rate constant, the flames were partially blown off near the outer wall and finally each flame linked together and formed a tubular-like flame[6,7].

B. Pressure Loss Comparison[11]

Figure 7 shows pressure losses of $\phi10h1$ original-sized flat-flame and swirling-flame combustors at injectors, without combustion. In the case of flat-flame combustor, pressure loss was estimated for double-porous-plates used as an injector and a rectifier. The flat-flame combustor had much lower pressure loss than the swirling-flamer combustor. At the design air mass flow rate of $\dot{m}_a$ =0.037g/s, the pressure loss of swirling-flamer combustor was 0.78%, in contrast, that of flat-flame combustor was only 0.10%, almost one eighth of another. Thus, the flat-flame burning method is effective method to stabilize micro flame with keeping low pressure loss.

Based on these considerations along 4 prerequisites for ultra-micro combustors, we concluded that the flat-flame burning method was superior to the swirling-flamer burning method synthetically.

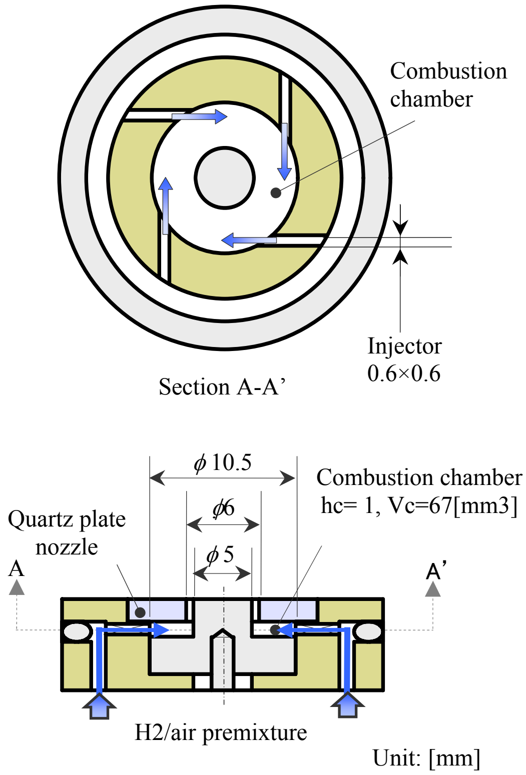


Fig.6(a) Schematic of swirling-flamer ultra-micro combustor

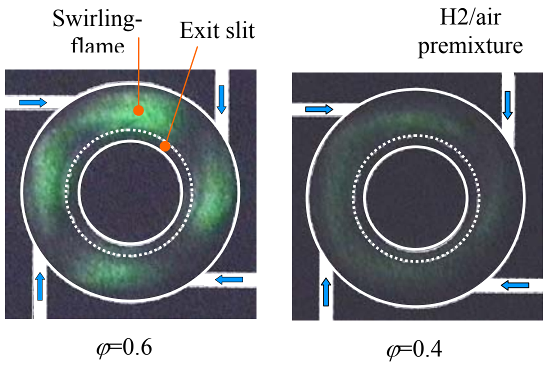


Fig.6(b) Image intensifier photographs of hydrogen/air swirling-flamers (exposure time:1/30[s], $\dot{m}_a$=0.035[g/s])

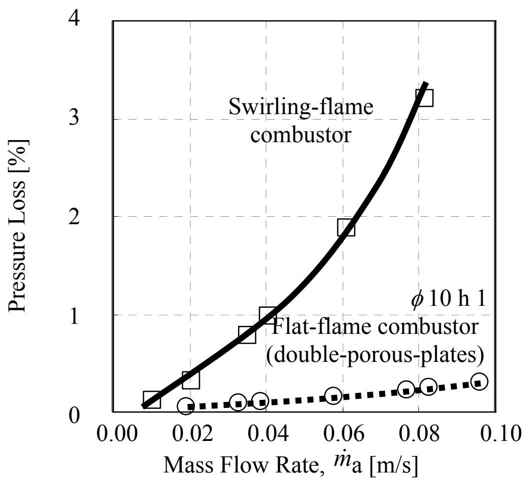


Fig.7 Pressure losses at injectors of flat-flame and swirling-flamer ultra-micro combustors without combustion[11)]

Development of an Engineering-Model of Hydrogen-Fueled Ultra-micro Combustor

Here we are moving onto the discussion about development of an engineering-model hydrogen-fueled ultra-micro combustor, to ground on concerns so far we mentioned.

A. Concept

Figure 8 (a) and (b) show a schematic and an appearance of an engineering-model of hydrogen-fueled ultra-micro combustor. The flat-flame burning method was adapted due to its suitability for the ultra-micro combustor by taking previous study[6, 7, 11)] into account. It will be installed onto UMGT as represented in Fig.9. Besides, Fig.9 shows the burning condition of the engineering-model combustor. The values were determined by referring to the MIT's concept, and further, by corresponding incoming premixture velocity into the combustion chambers in the light of the experimental facility condition; at room temperature and atmospheric pressure.

The point of this UMGT layout is that the combustor was isolated from the compressor and turbine, which induces plainness of not only combustor structure but also heat insulation system. In other words, the study for development of an engineering-model combustor is released from the issue of heat transfer from combustor to other components, one of the biggest problems causing degradation of performance in UMGT system[12)].Thus, in the matter of heat insulation, only combustor chamber itself should be simply insulated.

A simple disc type combustion chamber was employed for the engineering-model flat-flame combustor. Its inlet and outlet were connected to one direction toward a compressor/turbine side to make UMGT concise and flat on the grounds that those components were laid out on the same plane surface.

It should be noted that radial exhaust annuler type, in contrast, was used for the prototype-model flat-flame combustors in order to simplify production, measurement and observation of the flame. Also, flat-flame is formed on the top of porous plate in the engineering-model combustor, as well as in prototype-model ones. As show in Fig.8, a spark type igniter was inserted into the combustion chamber.

Details about the hydrogen-fueled engineering-model flat-flame combustor were given in points of following considerations; size, material, velocity, pressure loss and prevention of flashback.

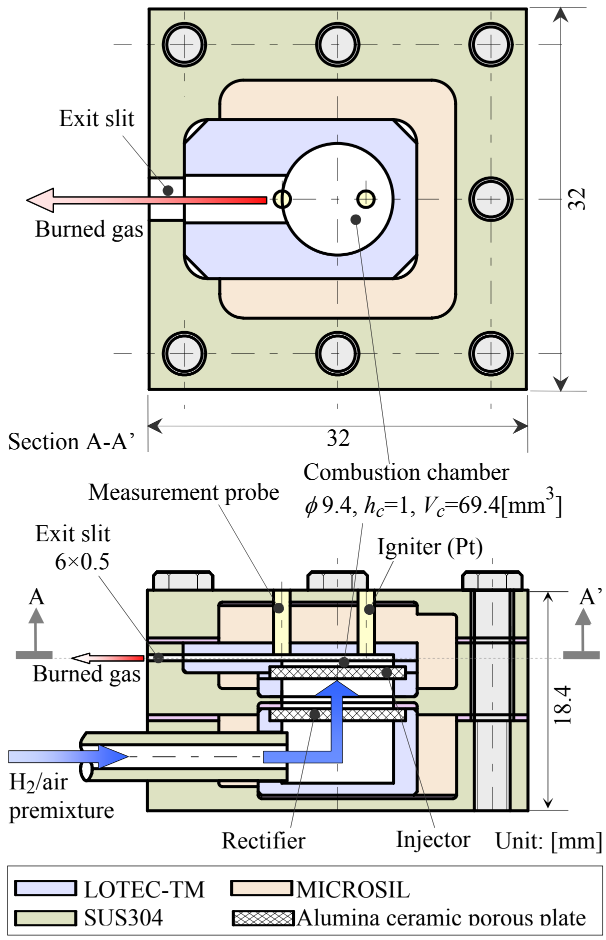


Fig.8(a) Schematic of an engineering-model of hydrogen-fueled flat-flame ultra-micro combustor

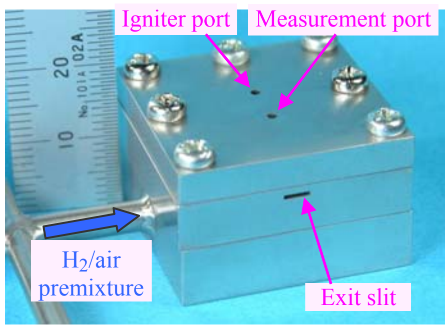
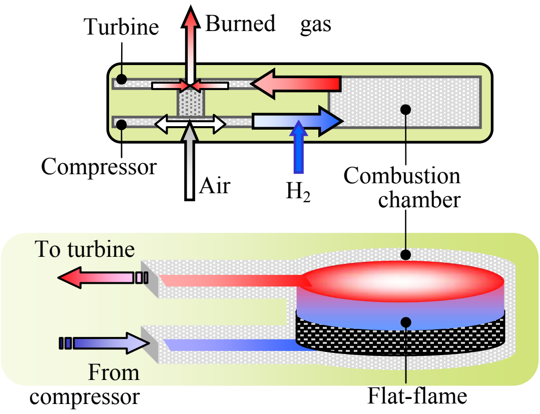


Fig.8(b) Appearance of an engineering-model of hydrogen-fueled ultra-micro combustor



Burning Condition	
At Room Temperature, Atmospheric Pressure	
Fuel	Hydrogen
Combustor Exit Temperature, T_{ex}	1600 [K]
Pressure Ratio	1
Air Mass Flow Rate, $\dot{m}_a$	0.037 [g/s]
Equivalence Ratio,	0.4
UMGT Power Output, W_c	16 [W]

Fig.9 Combustion chamber layout in UMGT and burning condition of an engineering-model ultra-micro combustor

B. Size

The combustion chamber of the engineering-model combustor had a height of 1mm and a volume of 69.4mm^3. Those values were equivalent to the original-sized prototype-model flat-flame combustor of high flame stability and combustion efficiency exceeding 99.5% around design point[6)]. Additionally the combustion chamber with 2mm height is examined in order to understand space heating rate effects by changing combustion chamber size.

C. Materials

The combustor consisted of 3 layers; LOTEC-TM (ceramic), MICROSIL (microporous insulation) and stainless steel following order of the layout from the inside as shown in Fig.8. Table1 gives properties of each material. This triple layer structure was required overall high heat-insulation, heat-resistant and strength. LOTEC-TM has good heat-resistant and machinability, yet little porosity. A stainless steel case was adopted because of its strength and relatively high property in heat-insulation, strength and corrosion-resistant. The opening space between LOTEC-TM and stainless steel case was filled up with MICROSIL of excellent heat-insulation.

From rough calculation of heat transfer, MICROSIL is required to be thicker than 3 mm around the combustion chamber to keep the combustor outer wall at almost room temperature. In fact, previous experiments with a prototype combustor gave a result that the 3mm-thick MICROSIL nozzle adequately prevented heat loss via the nozzle[6, 9)]. Alumina ceramic porous plates of good heat-, corrosion- and oxidation-resistant were served as an injector and a rectifier as well as in prototype combustors.

Table.1 List of properties of materials

	LOTEC-TM (Machinable Ceramics)	MICROSIL (Microporous Insulation)	Stainless Steel
Main Composition	Aluminum Titanate ($Al_2O_3 \cdot TiO_2$)	Ultra-fine Silica Powder/ Glass Reinforcing Fiber (SiO_2)	SUS304
Max Use Temperature	1500 [°C]	950 [°C]	400 [°C]
Thermal Conductivity	2.6 [W/(m・K)] at 1200[℃]	0.038 [W/(m・K)] at 800[℃]	19 [W/(m・K)]
Porosity	4.6 [%]	High	0

D. Velocity

The velocity and the Reynolds number of incoming premixture at the porous plate injector into the combustion chamber were calculated as about 0.68m/s and 120 for design mass flow rate of $\dot{m}_a$=0.037g/s at room temperature and atmospheric pressure. At steady status in heat transfer, incoming premixture were assumed to be preheated up around 600K to take previous experiment into consideration[9)]. Then the velocity and the Reynolds number of incoming preheated premixture into the combustion chamber were anticipated to become 1.3m/s and 230 at this condition. It was considered that the incoming flow satisfied a velocity requirement to hold flat-flame in 1mm-height ultra-micro combustion chamber. Meanwhile, a narrow exit slit was designed to increase exhaust velocity to about 100m/s by accordance to ordinal apprehension.

E. Pressure Loss

Commonly pressure loss of micro gas turbines at combustors is about 3 to 5%. While total pressure loss of the engineering-model combustor was calculated as only 0.39% for design mass flow rate of $\dot{m}_a$=0.037g/s, at room temperature and atmospheric pressure, and without combustion. It achieved lower amount than the general requirement.

F. Prevention of Flashback

One of the most indispensable requirements for premixture type combustor design is flashback prevention. Especially when we use hydrogen fuel, that has notably high burning velocity, more cautious consideration about perils of the flashback is needed. In the case of flat-flame, the velocity of incoming premixture into the combustion chamber is expected to be lower than burning velocity due to the basic principle of this burning method[4)]. As to this engineering-model combustor, the burning velocity of about 1.3m/s known as the measurement value is actually bigger than the incoming premixture velocity at the design equivalence ratio of φ=0.4, the mass flow rate of $\dot{m}_a$=0.037g/s, room temperature and atmospheric pressure. That seems flashback might occur in this combustor, however, it can be said that no flashback will occur due to a following reason; tiny pore diameter of porous plates comparing with quenching distance.

Quenching distance of the premixed flame is about 0.7 mm[13)] at design equivalence ratio of φ=0.4, room temperature and atmospheric pressure. On the other hand, pore diameter of porous plates is given average of 0.23mm or maximum of 0.26mm by the manufacturer, which is much shorter than quenching distance. Hence flame cannot pass through the injector porous plate.

However the objection will no doubt be raised that quenching distance is shortened at high temperature. In fact, previous experiments with the prototype-model combustor gave the result that heat transfer from the combustion chamber made the injector porous plate and premixture preheated to about 600K[9)]. Little is known about quenching distance in this high temperature region, yet quenching distance might become shorter than the pore diameter. We have to say it is beyond the scope of this paper to discuss about it. Empirically, no flashback had occurred in any previous experiments with the prototype- model flat-flame combustors.

Here, other method to prevent flashback should be argued: Use of double porous plates can be helpful for that. Even though flashback through the injector porous plate is actually happened, it must be stopped in the rectifier porous plate because its condition is at almost room temperature and there quenching distance can return to be longer than the pore distance. If flashback happens, the rectifier porous plate can be changed other one with smaller pore distance.

Conclusion

- ✓ Reviewing the problems in the development of ultra-micro combustors suggested that the most important requirement is to achieve high-space-heating-rate combustion. It improves heat loss rate and residence time.

- ✓ Suitability of flat-flame burning method for UMGT was confirmed by comparing with swirling-flamer burning method in the prerequisites for practical ultra-micro combustors. The flat-flame burning method is superior in term of the pressure loss.

- ✓ An engineering-model of hydrogen-fueled flat-flame ultra-micro combustor with the combustion chamber volume of 69.4mm^3 and height of 1mm was designed for a 16W-output UMGT. By concerning heat loss and transfer from the combustor to the compressor and turbine, the combustor was consisted of 3 materials; LOTEC-TM (machinable ceramic), MICROSIL (microporous insulation) and stainless steel. The combustor was isolated from the compressor and turbine. Pressure loss in the combustor was calculated as about 0.39% at the design operation point, without combustion.

Nomenclature

C_p	specific heat at constant pressure
d_i	inner diameter
d_o	outer diameter
D	diffusion coefficient
Da	Damköhler number
h_c	height of combustion chamber
H_{ex}	total enthalpy at combustor exit
H_{in}	total enthalpy at combustor entrance
HL	heat loss
HLR	heat loss ratio
HT	overall heat transfer coefficient from combustor to the surroundings
ΔH	heat of combustion
$\dot{m}$	total mass flow rate
$\dot{m}_a$	air mass flow rate
$\dot{m}_f$	fuel mass flow rate
P_c	pressure of combustion chamber
Q	heat release rate
Re	Reynolds number
S	cross section area of combustor
SHR	space heating rate
ST	stoichiometric fuel/air ratio
T_{in}	temperature at combustor entrance
T_{ex}	temperature at combustor exit
ΔT	temperature difference between combuster outer wall and the surroundings
U_c	characteristic velocity

v	mean flow velocity of premixture through combustion chamber
V_c	volume of combustion chamber
W_c	corresponding UMGT output power
α	constant
β	constant ($0<\beta<1$)
φ	equivalence ratio
ℓ	characteristic length of combustor
ν	kinematic viscosity
ρ	density of gas in combustion chamber
τ_{res}	residence time in combustion chamber
τ_{chem}	characteristic chemical reaction time

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Reference

1) Epstein, A. H. et al.: Micro-Heat Engines, Gas Turbines, and Rocket Engines -The MIT Microengine Project-, 28th AIAA Fluid Dynamics Conference, 4th AIAA Shear Flow Control Conference, 1997, AIAA 97-1773.
2) Pello, A. C. F.: Micro-Power Generation Using Combustion: Issues and Approaches, Proceedings of the Combustion Institute, Vol. 29, 2002, pp. 883-899.
3) Yuasa, S.: Current State and Problems of Ultra micro Hydrogen Combustors (in Japanese), *Journal of the Gas Turbine Society of Japan*, Vol. 29, No. 4, 2001, pp. 247-254.
4) Yuasa, S., Oshimi, K.: Concept and Experiment of a Flat-flame Micro-combustor for Ultra Micro Gas Turbine, 38th AIAA/ASME /SAE/ASEE Joint Propulsion Conference and Exhibit, 2002, AIAA 2002-3771.
5) Yuasa, S., et al.: Concept and Combustion Characteristics of Ultra-micro Combustors with Premixed Flame, Proceeding of the Combustion Institute, Vol. 30, 2004, pp. 2455-2462.
6) Yuasa, S. et al.: Specified Problems and Development of Prototypes of Ultra-micro Combustor, Proceedings of the 18th International Symposium on Air Breathing Engines, 2005, ISABE 2005-1272.
7) Yuasa, S. et al.: Issues for Developing Ultra-micro Combustors for UMGT: Heat Loss, Combustion Method and Fuel, Proceedings of the 19th International Symposium on Air Breathing Engines, 2007, ISABE2007-1167.
8) Kanury, A.M.: *Introduction to Combustion Phenomena*, Gordon and Breach Science Publishers, New York, 1982, pp.130-131.
9) Oshimi, K., and Yuasa, S.: Evaluation of Heat Transfer in Flat-flame Ultra-Micro Combustor for Ultra Micro Gas Turbine (in Japanese), *Journal of the Gas Turbine Society of Japan*, Vol.33, No.3, 2005, pp.221-229.
10) Yuasa, S. et al.: Consideration on Burning at High Space Heating Rate in Ultra-Micro Combustors for UMGT (in Japanese), Proceedings of the 45th Symposium (Japanese) on Combustion, 2007, pp. 108-109.
11) Wong, S. F.: Combustion Characteristics of Swirling-flamer Ultra-Micro Combustors for UMGT (in Japanese), master thesis dissertated to Tokyo Metropolitan Institute of Technology, 2006, pp.57-58.
12) Oshimi, K., Yuasa. S.: The effect of the heat transfer between the components of Ultra Micro Gas Turbine on its performance (in Japanese), *Journal of the Gas Turbine Society of Japan*, Vol.31, No.5, 2003, pp. 340-345.
13) Hirano, T.: Combustion (Nenshougaku, in Japanese), Kaibundou, Tokyo, 1986, pp.131.