

# UNIFIED PRACTICAL AERO-THERMODYNAMIC DESIGN APPROACH FOR MEMS BASED MICRO COMBUSTORS

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**Abstract:** This paper describes aero-thermodynamic design, micro fabrication and combustion test results for a single crystal silicon premixed fuel micro-scale can combustor. The micro-scale can combustor was fabricated by the silicon bulk micromachining technology. Hydrogen fuel - air premixing was used for combustion test. A proposed aero-thermodynamic design approach on the basis of the three models (burning velocity model, well - stirred reactor and combustion loading parameter models) provide physical interpretation for the experimentally obtained operating space of stable combustion. Furthermore, this approach provides unified physical interpretation for the stable combustion operating spaces obtained from various kinds of geometrical scale and configuration of the micro-scale combustors. Therefore, it is demonstrated that the proposed aero-thermodynamic approach has important role to predict preliminary aerodynamic design performances of new micro-scale combustors.

**Keywords:** Micro-scale can combustor, Burning velocity, Well - stirred reactor, Combustion loading parameter

## INTRODUCTION

An excellent review by Epstein described technical challenge of MIT mm-scale silicon micro gas turbine engine for portable electric power generation and micro air vehicle propulsion systems [1]. According to the series research of micro-scale silicon annular combustor by MIT, overall performance and some combustion physics support the micro-scale combustor design have been clarified [1-4]. Spadaccini et al. concluded that the operating space of the micro-scale combustor was expressed as a function of Damköhler number ( $Da$ ), thermal loss (combustion efficiency) and power density. Furthermore, technical issues for the design of the micro-scale combustor were pointed out as follows [4].

[1] *Mass flow rate over the condition of Damköhler number  $<1$  ( $Da < 1$ ), induces flame extinction.*

[2] *The large recirculation zone results in decreased  $Da$ .*

[3] *The large surface to volume ratio of a micro-scale combustor makes non adiabatic operation.*

This paper tried to apply an aero-thermodynamic approach on the basis of the burning velocity, the well - stirred reactor, and the combustion loading parameter models to the micro-scale combustor design. The proposed silicon micro-scale can combustor may be used for a micro-scale turbo-machinery as a future application. However, the main purpose of the paper is to provide a unified practical aero-thermodynamic design method for the micro-scale combustor on the basis of a rigorous physical background. In order to establish the aero-thermodynamic model for micro-scale combustor, the correlation between the geometrical scale and configuration, and the aerodynamic parameters which provide design operating space of stable burning, was investigated in detail. Finally, it will be concluded, from the practical engineering view points, the model can provide unified design guideline for the micro-scale combustors

having different geometrical scale and configurations.

## DESIGN METHOD

### Burning velocity model

A new combustor design may be based on the large extent on past experience. A one of the useful way in which the past experience can be accumulated is by the use of diagrams. In the diagram, combustion efficiency data from all known combustors are correlated against all the relevant variables. Figure 1 shows such a diagram, which was first proposed by Lefebvre on the basis of the burning velocity model. The combustion efficiency can be expressed as a function of burning velocity [5],

$$\eta_c = \frac{\text{heat released in combustion}}{\text{heat available in fuel}} \propto \frac{S}{U_{ref}}. \quad (1)$$

If  $U_{ref}$  can be expressed in terms of  $\dot{m}_A, P_3$  and  $A_{ref}$ , and  $S$  in terms of laminar burning velocity, Eq.(1) becomes [5],

$$\eta_c = f(\theta) = f \left[ \frac{(P_3)^{1.75} A_{ref} (D_{ref})^{0.75} \exp(T_3/300)}{\dot{m}_A} \right]. \quad (2)$$

Horizontal line in Fig.1 indicates the reaction rate parameter ( $\theta$  parameter) defined by the function,

$$\theta \equiv \frac{(P_3)^{1.75} A_{ref} (D_{ref})^{0.75} \exp(T_3/300)}{\dot{m}_A}. \quad (3)$$

Vertical line indicates the combustion efficiency. In Fig.1, enclosed areas include experimental data obtained from a large number of can (or “tubular”), can-annular (or “tuboannular”), and annular combustors. Typical values of the combustors for modern aircraft engines [7-9] and MEMS counterparts by MIT [1-4] and SIMTEC [6] can be plotted within the enclosed region determined by Lefebvre [5]. Available experimental data for the combustion efficiencies of the micro-scale combustors are extremely limited. From the view point of the first approximation, however, it is expected that the large-

scale combustors and micro-scale counterparts obey unified physics and scaling law on the basis of the burning velocity model. Appropriate values of  $A_{ref}$  and  $D_{ref}$  can be obtained from Fig.1 by reading off  $\theta$  parameter at a point along a horizontal axis within the enclosed area at required combustion efficiency. Then, the values of  $A_{ref}$  and  $D_{ref}$  can be obtained by substituting into  $\theta$  parameter the values of  $P_3$ ,  $T_3$  and  $\dot{m}_A$  corresponding to the required engine specifications.

According to the experimental data obtained from MIT and SIMTEC micro-scale annular combustors, typical values of the combustion efficiencies under ambient pressure are distributed from 40% to 90% [1-4,6]. Therefore, a target conservative value of the combustion efficiency is to be selected as high as 70% for our combustor design. This approach seems to give an eye-ball sense for the design. Once, the values of the combustion efficiency,  $P_3$ ,  $T_3$  and  $\dot{m}_A$  corresponding to the required design specification are selected, the product value of the geometrical scale of  $A_{ref}$  and  $D_{ref}$  can be determined from Eq. (3).

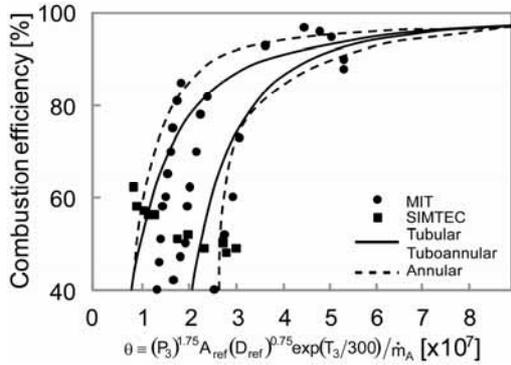
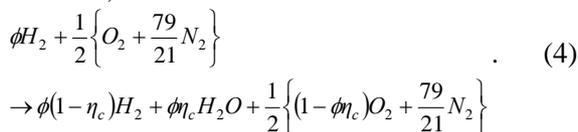


Fig. 1: Design chart for combustion efficiencies against relevant variables on the basis of burning velocity model (Lefebvre's chart [5]).

### Well-stirred reactor model

One of a quantitative expression for the combustion process in a combustor is to assume a combustion zone as the well-stirred reactor model [5,7-10]. However, a technical drawback of the well-stirred reactor model is that the heat-release rates are related to the reaction temperature [5]. Therefore, the combustion efficiency must be known, a priori, in order to estimate the reaction temperature. The combustion efficiency predicted from the burning velocity model (Fig.1) is useful measure to supplement the well-stirred reactor model. A simplified atom-balance equation for the overall lean-combustion reaction of the hydrogen – air pre-mixture fuel is expressed as,



The sum of the product molecular numbers is

$$N_{total} = \frac{50}{21} + \phi \left( 1 - \frac{1}{2} \eta_c \right) \quad (5)$$

The static temperature and the combustion efficiency can be expressed as a linear equation by using the energy balance equation for the static enthalpy of reactant and product gases [7-9],

$$T = T_3 + \eta_c (T_{AFT} - T_3) = T_3 + \eta_c \left( \frac{\phi f_{st} h_{H_2}}{C_p} \right) \quad (6)$$

Using equations (4) to (6), the volumetric mass flow rate consumption of the hydrogen – air pre-mixture fuel can be expressed by a modified Arrhenius equation for the overall combustion reaction,

$$RR_{H_2} = M_{H_2} Ar \exp \left( -\frac{E_a}{RT} \right) \left( \frac{p_3}{RTN_{total}} \right)^3 \phi^2 (1 - \eta_c)^2 (1 - \phi \eta_c) \times 10^{-15} \quad (7)$$

The conservation of fuel mass is applied to the steady flow well-stirred reactor control volume, corresponding to the recirculation zone of the flameholder wake, in order to determine an alternative form of the volumetric mass flow rate consumption:

$$RR_{H_2} = \left( \frac{\phi f_{st} \dot{m}_E}{V_{WSR}} \right) \eta_c \quad (8)$$

### Combustion loading parameter

In gas turbine combustor practice, the well-stirred reactor concept is applied to the entire volume of the chamber [7-10]. When so applied, the common solution of the two equations represents equating the two equations for  $RR_{H_2}$  given by Eqs. (7) and (8):

$$RR_{H_2} = M_{H_2} Ar \exp \left( -\frac{E_a}{RT} \right) \left( \frac{p_3}{RTN_{total}} \right)^3 \phi^2 (1 - \eta_c)^2 (1 - \phi \eta_c) \times 10^{-15} = \left( \frac{\phi f_{st} \dot{m}_A}{V_{chamber}} \right) \eta_c \quad (9)$$

Rearranging the Eq.(9) by eliminating  $RR_{H_2}$  and by putting  $A_{ref} D_{ref} \equiv V_{chamber}$  :

$$I = \frac{\dot{m}_A}{A_{ref} D_{ref} (P_3)^3} = \frac{M_{H_2} Ar \exp \left( -\frac{E_a}{RT} \right) \phi (1 - \eta_c)^2 (1 - \phi \eta_c) \times 10^{-15}}{\eta_c f_{st} (\overline{RTN_{total}})^3} \quad (10)$$

This is called the combustion loading parameter CLP [7-10]. The CLP reflects the influence of the airflow rate, combustor volume and static pressure on the combustion flame stability. By fixing six parameters, i.e.,  $M_{H_2}$ ,  $f_{st}$ ,  $Ar$ ,  $R$ ,  $E_a$  and  $\phi$ , and the two independent parameters  $T$  and  $\eta_c$ , Eq.(10) can be

solved for corresponding values of  $I = \frac{\dot{m}_A}{A_{ref} D_{ref} (P_3)^3}$ .

### FABRICATION

Table 1 shows specification of the combustor. Figure 2 shows a cross-sectional view of the prototyped silicon micro-scale can combustor. The micro-scale can combustor is composed of micro-fabricated seven silicon wafers. A 500 $\mu$ m-thick silicon wafer is selected as a starting substrate. Both sides of

the silicon wafer are patterned by ultraviolet (UV) lithography and etched by the inductively coupled plasma-reactive ion etching (ICP-RIE). Each wafer is aligned and bonded together to form a multilayer silicon combustor assembly. These micro-structures are fabricated by ICP-RIE.

Table 1: Design specifications for micro-scale can combustor.

Micro scale can combustor	
Length ( $D_{ref}$ )	$1.8 \times 10^{-3}$ m
Volume ( $V_{chamber}$ )	$277 \times 10^{-9}$ m <sup>3</sup>
Cross-sectional area ( $A_{ref}$ )	$25.2 \times 10^{-6}$ m <sup>2</sup>
Inlet pressure ( $P_3$ )	101.3 kPa
Inlet temperature ( $T_3$ )	288 K
Mass flow rate ( $\dot{m}_A$ )	$0.2 \times 10^{-3}$ kg/s
Efficiency ( $\eta_c$ )	$\geq 70$ %
Exit temperature ( $T_g$ )	1300 K

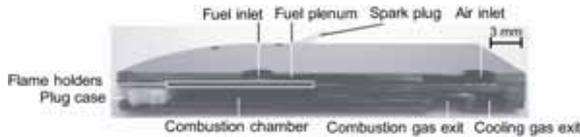


Fig. 2: Cross-sectional views of prototyped silicon micro-scale can combustor.

## EXPERIMENTAL RESULTS

The micro-scale combustion tests were performed with premixed hydrogen - air fuel. Figure 3 shows the plots of combustor exit temperature with the variation of equivalence ratio. Figure 4 shows the plots of corresponding overall combustor efficiency. Figure 5 shows the combustion inefficiency against the equivalence ratio. The combustor produced the maximum exit gas temperature of 1350K for mass flow rate of 0.2g/s under ambient pressure. The maximum overall efficiency is 68% at the exit gas temperature of 1200K. The values of  $\leq 10\%$  were obtained regardless of the equivalence ratio. The contribution of combustion inefficiency due to the unused chemical energy is relatively small. This may be an acceptable or borderline level for the micro-scale turbo-machinery application. After several hour operations, a significant permanent deformation due to creep and a fatal failure due to discontinuous structure of the members (due to the stress concentration) were not observed in the combustor.

## DISCUSSION

Figures 6 depicts a diagram which was first proposed by Lefebvre on the basis of the burning velocity model. Experimental data for micro-scale and conventional combustors are plotted within the region predicted by Lefebvre. Therefore, the combustion efficiency has strong correlation with the  $\theta$  parameter defined in Eq.(3) regardless of the scale and

geometrical configurations of the combustors. Figure 7 depicts the stable combustion limit as a function of the equivalence ratio and the CLP. The experimental data obtained from MIT, SIMTEC and present work are plotted within the predicted stable combustion limits regardless of the difference in the geometrical configurations of the combustors. Therefore, it is concluded, from the practical engineering view points, the aero-thermodynamic design on the basis of the burning velocity, the well - stirred reactor and the combustion loading parameter models can provide unified design guideline for the micro-scale combustors having different geometrical scale and configurations. A design recommendation for a new micro-scale combustor will be summarized as follows.

- [1] Specification of combustion efficiency
- [2] Calculation of combustion chamber geometrical scale
- [3] Prediction of stable operation space of combustor

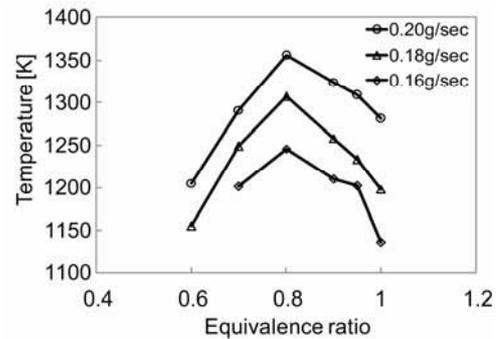


Fig. 3: Experimental measurements for combustor exit temperatures with the variation of equivalence ratio.

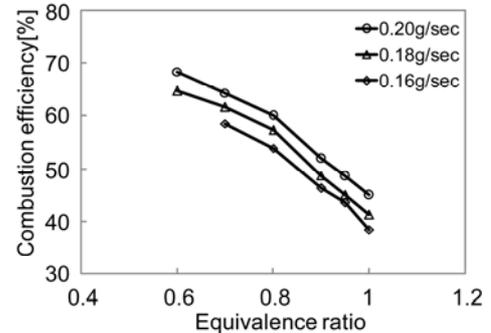


Fig. 4: Experimental measurements for combustor efficiencies with the variation of equivalence ratio.

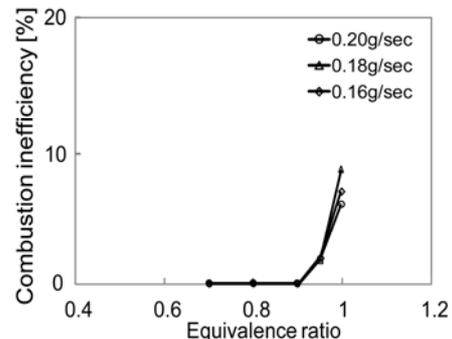


Fig. 5: Combustion inefficiency due to unused chemical energy with the variation of equivalence ratio.

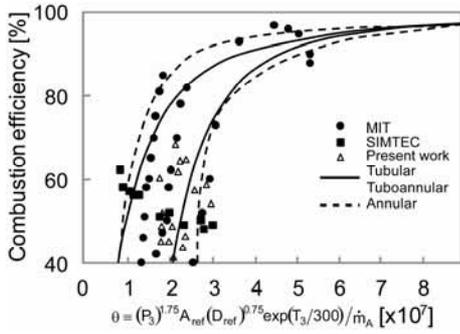


Fig. 6: Correlation between combustion efficiencies for silicon micro-scale combustors and Lefebvre's  $\theta$  parameters [5].

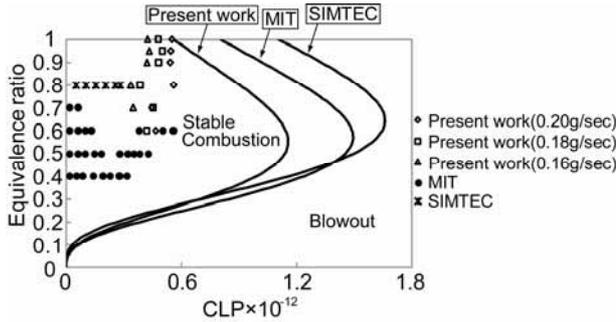


Fig. 7: Comparison of predictions and experimental results for stable combustion operating spaces obtained from past and present works (previous works were reported by MIT[1-4] and SIMTEC[6]).

## CONCLUSION

The aero-thermodynamic performance of the micro-scale can combustor was designed on the basis of the burning velocity, the well - stirred reactor and combustion loading parameter models. The stable combustion operation spaces were experimentally related to the geometrical configuration and inlet thermodynamic quantities of the prototyped micro-scale can combustor. The proposed aero-thermodynamic model provided the rigorous physical interpretation for the performance of the micro-scale combustors investigated by the authors, and previous works done by other research institutions. It was concluded the model can provide unified design guideline for the new micro-scale combustors having different geometrical scales, configurations, and unknown aero-thermodynamic performances.

## NOMENCLATURE

$A_r$  = Arrhenius constant

$C_p$  = constant pressure specific heat

$D_{ref}$  = combustor reference length

$E_a$  = activation energy

$f_{st}$  = stoichiometric mass -basis fuel-air ratio

$M_{H_2}$  = molecular weight of hydrogen

$\dot{m}_E$  = mass flow rate of entrainment of fresh mixture into the bluff body wake region

$N_{total}$  = total product mol number

$R$  = universal gas constant

$RR_{H_2}$  = volumetric mass rate of consumption of hydrogen

$S_u$  = combustion flame velocity

$T_{AFT}$  = adiabatic flame temperature

$U_{ref}$  = combustor reference velocity

$V_{WSR}$  = bluff body wake region volume as a well stirred reactor

$\phi$  = equivalence ratio

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