An Experimental Study of the Ignition and Combustion Mechanisms in a Pulse Combustor*

(A New Approach to a Wide-Range and Low-Noise Pulse Combustor)

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A new method is proposed to obtain a wide-range and low-noise-level pulse combustion in the case of natural ventilation. It is found that the supply of a rich propane-air mixture, instead of pure fuel, which is outside the rich inflammability limit and has an equivalence ratio of 3.0 in the present experiment, can realize a higher combustion intensity of 53.4 MW/m^3 and a larger turn-down ratio of 4.5 than those of the usual pulse combustors. A rather silent pulse combustion, whose noise level is 55–70dB(A) without any silencer, is possible by operating the present combustor at a 15–35% partial load. The volumetric efficiency of a pulse combustor is defined by the ratio of the total volume of fresh mixture and air supplied per cycle at NTP to the volume of the combustor, and is found to vary within the range of 4–12%, corresponding to the minimum and maximum combustion loads, respectively. As a result, the volumetric efficiency may be expected to be an important design parameter of the pulse combustor.

Key Words: Combustion, Pulse Combustor, Turn-down Ratio, Combustion Noise, High Combustion Intensity, Volumetric Efficiency

1. Introduction

In recent years, the use of pulse combustion systems has increased because of their excellent thermal efficiencies, high combustion intensities, and low pollutant levels. Since these devices also exhibit small turn-down ratios and extremely high noise levels, however, indispensable for the solution of the problems and for the wide practical use of the pulse combustor are fundamental investigations on the physical and chemical phenomena involved in the periodic ignition and burning processes. For these purposes, many experimental and theoretical studies have been made^{(1)~(7)}, but the defects seem to be little solved.

In the previous paper of this study⁽⁸⁾, a combustible propane-air mixture of an equivalence ratio of 1.1 was forced into the basic two-dimensional and flapper-valved pulse combustor. This approach might

serve to eliminate the mixing process of fuel with air before ignition, which was considered to be the main part of the physical process, and to simplify understanding of the ignition and combustion mechanisms. The results showed that the cyclic ignition of the mixture was caused by a direct contact and rapid mixing with residual hot burned gases, being regarded as a spontaneous ignition. Also shown was a possibility of increasing the turn-down ratio.

In this paper, by taking into account the risk of dealing with a combustible mixture, which may prove fatal for a practical application of the pulse combustor, a rich propane-air mixture outside the inflammability limit is supplied, instead of both a combustible mixture and pure fuel, under the condition of the natural ventilation of secondary air. In the following, the possibility of getting a wide-range and low-noise-level pulse combustion is experimentally examined by varying the equivalence ratio of the rich mixture and the tailpipe geometry. The results of measurements of the pulsating limits, CO emission concentration, and the noise level without any silencer are presented, and a general and practical estimation of the combustor performance is made based on the

* Received 18th May, 1987. Paper No. 86-0990 B

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volumetric efficiency of a pulse combustor.

Nomenclature

A : cross-sectional area of tailpipe	[cm ²]
[CO] : CO concentration in exhaust gas	[vol%]
f_0 : pulsating frequency of combustor	[Hz]
ΔH : heating value of fuel	[MJ/m ³]
L : length of tailpipe	[m]
Q_{apN} : flow rate of primary air at NTP	[L/min]
Q_{asN} : flow rate of secondary air at NTP	[L/min]
Q_{atN} : flow rate of total air at NTP, $=Q_{apN} + Q_{asN}$	[L/min]
Q_{tN} : flow rate of fuel at NTP	[L/min]
Q_{tN} : total fresh inflow, $=Q_{atN} + Q_{tN}$	[L/min]
q : heat release rate	[MJ/h]
q_{max} : maximum heat-release rate, given by Eq. (2)	[MJ/h]
TDR : turn-down ratio, defined by $(Q_{tN})_{max}/(Q_{tN})_{min}$	[—]
V : volume of combustion chamber	[m ³ , cm ³]
η_v : volumetric efficiency of pulse combustor, defined by Eq. (1)	[—]
$(\eta_v)_{max}, (\eta_v)_{min}$: maximum and minimum volumetric efficiency of pulse combustor, respectively	[—]
ϕ_p : equivalence ratio of rich mixture	[—]
ϕ_t : total equivalence ratio	[—]
μ_t : total air ratio, $=1/\phi_t$	[—]
λ_{th} : stoichiometric air fuel ratio in volume	[—]

Fig. 1 Schematic of present experimental system

2. Experimental Facility and Procedure

Figure 1 presents a schematic of the experimental system used in this study, and Fig. 2 a nozzle detail of the flapper-valved pulse combustor. The main part of the combustor has a rectangular cross section of 60 mm (width) $\times$ 50 mm (depth) and a height of 80 mm. A two-dimensional contraction section of 50 mm in depth and 15 mm in length follows the square part and joins it to the tailpipe. The volume of the combustion chamber is a constant of $V=260\text{cm}^3$, whereas four geometrical configurations of the tailpipe are employed; they are expressed by the notation A/L , where A is the cross-sectional area [cm²] and L is the length [m] of the tailpipe, and are given by $A/L=5.0/2.0$, $5.0/1.0$, $2.5/2.0$, and $2.5/1.0$.

A rectangular stainless steel foil of dimensions of 40 mm $\times$ 48 mm and of 0.05 mm thickness is used as a flapper-valve in combination with a backer plate made of a stainless steel porous plate with dimensions of 40 mm $\times$ 50 mm and thickness of 5 mm. The clearance between the nozzle exit and the backer plate is 2 mm, indicating the range of the flapper-valve move-

Fig. 2 Nozzle detail of flapper-valved pulse combustor

ment.

Propane and compressed primary air enter into the mixing chamber to form a rich mixture, whose equivalence ratio is set by measuring the flow rates of fuel and primary air, Q_{fN} and Q_{apN} , respectively, the subscript N representing the rate to be reduced to normal temperature and pressure (NTP). In this experiment, a rich mixture outside the flammability limit is used for safety from the flashback during an explosion period, and is supplied into the combustion chamber through three tubular nozzles of 3 mm inner diameter under a nearly constant charge pressure of 5 kPa. The secondary air is measured by the orifice flowmeter, on the other hand, and flows into the combustor with the rate, Q_{asN} , through a porous plate nozzle composed of ten holes of 4 mm in diameter.

Measurements of the pulsating limits, CO concentration in the exhaust gases, combustion noise level without any silencer, and the operating frequency of the combustor are obtained for this investigation. Rich and lean limits, beyond which a pulse combustion cannot operate, are measured by adjusting the secondary air flow rate with the flow control valve just upstream of the porous plate nozzle and the blower, respectively. The exhaust gases are sampled with a portable emission analyzer to give the average concentration of CO [vol%] within the resolution limit of 0.04%. The pulsating frequency is obtained from an FFT-analysis of the oscillating pressure, which is measured by a water-cooled, semiconductor pressure transducer installed in the combustor wall. Noise level measurements are also made with a sound level meter at a position 2 m apart from and normal to the combustor.

3. Experimental Results and Discussion

3.1 Pulsating limits and turn-down ratio

Figure 3 shows the influences of the equivalence ratio of a rich mixture and the tailpipe geometry on the pulsating limits of the combustor in the Q_{fN} - Q_{aLN} plane, where the rich and lean limits are presented by the symbols, $\bigcirc$ and $\bullet$, respectively. The rich limit is obtained by decreasing the secondary air flow rate with the flow control valve until a pulse combustion ceases, whereas the lean is reached by forcing the secondary air into the combustion chamber with the blower until pulsation stops. Heat-release rate, q , calculated under the assumption of a perfect combustion of fuel supplied, is also indicated in Fig. 3 as an ordinate, together with three lines of constant total equivalence ratio of $\phi_t = 1.5, 1.0$, and 0.5 for an easy estimation of the limit equivalence ratios. In Table 1, summarized are the minimum and maximum fuel flow rates, $(Q_{fN})_{\min}$ and $(Q_{fN})_{\max}$, and the turn-down ratio,

TDR , where the latter is defined by the ratio, $(Q_{fN})_{\max}/(Q_{fN})_{\min}$. Also involved in Table 1 are those results obtained by supplying a combustible mixture of $\phi_p = \phi_t = 1.1^{(8)}$.

(a) General features of pulsating limits

From Fig. 3, the lean pulsating limits may be given by a nearly constant value of $\phi_t = 0.5$. The values of ϕ_t at the rich limit, on the other hand, are found to vary from about $\phi_t = 1.0$ in the region near the minimum heat-release rate of 8.0~14.0 MJ/h to a value of $\phi_t = 1.3 \sim 1.4$ in the range of high heat-release rate, greater than 30.0 MJ/h. These results suggest that the rich pulsating limit in the low combustion intensity may depend on a different mechanism from that for the lean pulsation limit and the rich one in the high combustion intensity. By taking into account the great increase in the exhaust CO concentration in the region near the maximum fuel flow rate, which will be discussed later in this paper, both the lean limit and the rich limit of the high heat-release rate are considered to be caused mainly by an imperfect combustion. With respect to the rich limit near the minimum combustion load, since the condition given by $\phi_t = 1.0$ is presumed to be most favorable for combustion to continue, the latter may be expected to be governed by Rayleigh's criterion⁽⁹⁾.

(b) Effects of rich-mixture equivalence ratio

Effects of a rich-mixture equivalence ratio on the pulsating limits and TDR may be seen in the first two figures of Fig. 3 and the upper three lines of Table 1. When the tailpipes of almost the same geometrical configurations given by $A/L = 5.0/2.1$ and $5.0/2.0$ are used, the rich mixture of an equivalence ratio of $\phi_p = 3.0$ gives a smaller $(Q_{fN})_{\min}$ and a larger $(Q_{fN})_{\max}$ than those of $\phi_p = 1.1$ and 5.0 , resulting in a large turn-down ratio of $TDR = 3.8$. In the present experiment, pulse combustion cannot be obtained in the case that pure fuel of $\phi_p = \infty$ is supplied under natural ventilation. The above results show that the mixing process of fuel with fresh air before ignition may play an important role in the ignition and combustion mechanisms in the pulse combustor, and therefore, suggest that an optimum concentration of the rich mixture should be chosen depending upon the rate and strength of the mixing process particular to a given combustor system. For the present combustor, the optimum equivalence ratio is found to be $\phi_p = 3.0$.

(c) Effects of tailpipe geometry

An examination of Figs. 3(b)~(e) and Table 1 represents the following effects of the geometrical configuration of the tailpipe on the pulsation limits and TDR : the maximum fuel flow rate increases with a reduction of the cross-sectional area of the tailpipe from $A = 5.0 \text{ cm}^2$ to 2.5 cm^2 , while the minimum

decreases with increasing the length of the tailpipe from $L=1.0$ m to 2.0 m. As a result, the smaller the cross-sectional area and the longer the length of the tailpipe, the greater the TDR . Thus, the most favorable geometry of the tailpipe for the present combustor may be given to be $A/L=2.5/1.0$, when much importance is attached to the maximum heat-release rate, and to be $A/L=2.5/2.0$ in the case of accentuating both the effective heating area and the turn-down ratio. In the present experiment, the maximum combustion intensity of $66.7 \text{ MW/m}^3 (=5.7 \times 10^7 \text{ kcal/m}^3\text{h})$ and a rather large TDR of 6.5 , which are about twice and 2.7 times the usual pulse combustor, respectively, can be attained by supplying the rich mixture of $\phi_p=3.0$, instead of the usual pure fuel.

3.2 Average CO emission and practical pulsating limits

Figure 4 presents profiles of the average CO concentration with the fuel flow rate for four geometrical configurations of the tailpipe corresponding to the conditions given in Figs. 3(b)~(e), where $\phi_p=3.0$. The heat-release rate is also shown in the abscissa.

In Fig. 4, low CO emissions are obtained in the intermediate range of the heat-release rate for each tailpipe configuration. Decreasing the fuel flow rate to the minimum results in a slight increase of CO emis-

Table 1 Maximum and minimum fuel flow rates and turn-down ratio

A / L	ϕ_p	Q _f NL/min		TDR
		min	max	
5.0/2.1	1.1	3.5	5.7	1.6
5.0/2.0	5.0	2.0	4.4	2.2
5.0/2.0	3.0	1.6	6.0[5.0]	3.8[3.1]
5.0/1.0		2.5	10.0[7.5]	4.0[3.0]
2.5/2.0		1.6	10.4[7.0]	6.5[4.4]
2.5/1.0		2.0	11.4[9.0]	5.6[4.5]

(a) $A/L = 5.0/2.0$, $\phi_p = 5.0$

(b) $A/L = 5.0/2.0$, $\phi_p = 3.0$

(c) $A/L = 5.0/1.0$, $\phi_p = 3.0$

(d) $A/L = 2.5/2.0$, $\phi_p = 3.0$

(e) $A/L = 2.5/1.0$, $\phi_p = 3.0$

Fig. 3 Behavior of pulsating limits

Fig. 4 Profiles of mean CO concentration with fuel flow rate, $\phi_p=3.0$

sion, because of an imperfect combustion caused by a weak mixing due to an insufficient pressure boost. Increasing the fuel flow rate to a critical value, on the other hand, at which point the maximum fuel consumption rate due to perfect combustion is supposed to be reached, also causes an abrupt increase in CO emission. The critical values of the fuel flow rate for each tailpipe geometry may be simply evaluated by setting the threshold value for CO emission equal to 0.1%, which is about double the resolution limit of the CO-meter used, and are arranged in the square brackets in Table 1, together with the *TDR*'s calculated with the critical values. Consequently, the maximum combustion intensity and the maximum *TDR* are lowered, as a matter of course, to 53.4 MW/m³ and 4.5. However, these values are still sufficiently larger than the usual pulse combustor, by approximately 1.6 and 2 times, respectively.

3.3 Possibility of low noise pulse combustor

Combustion noise levels, measured at a point 2 m apart from the combustor without any silencer installed in either the supply or exhaust lines, are depicted in Fig. 5 for the same experimental conditions as those for CO emission measurements given in Fig. 4. Although some data show a slight scattering, Fig. 5 indicates that the noise level expressed in dB(A) increases almost linearly with the heat-release rate, depending mainly on the tailpipe cross-sectional area, and that a decrease in the latter from $A=5.0$ cm² to 2.5 cm² enables a slight noise reduction by about 5 dB(A).

It should be mentioned, here, about the following key features for noise reduction: by operating the present pulse combustor at a partial combustion load

Fig. 5 Variations of combustion noise level with heat-release rate, $\phi_p=3.0$

of 15~35%, a rather quiet pulse combustion can be accomplished without any silencer, whose noise level ranges from 55 to 70 dB(A). However, it should also be noted that this approach to a low-noise-level pulse combustion is only possible for such a combustor with a large turn-down ratio as the one used in the present experiment.

3.4 Volumetric efficiency of pulse combustor

In the preceding sections, an excellent pulse combustor with a large turn-down ratio and low noise level was found to be relatively easily obtained by supplying a rich mixture outside the rich inflammability limit, instead of pure fuel. However, as almost all the results obtained so far are characteristic of the present pulse combustor, it is difficult to make a general comparison about the combustor performance. This indicates the clear necessity of introducing such a common parameter as enabling a simple and full comparison among the pulse combustors with different specifications from each other. Generally, knowing the maximum fuel consumption rate beforehand, and, therefore, knowing the maximum heat-release rate for a given geometry of the combustor provides a great advantage in designing that pulse combustor. From this point of view, the pulsating limits shown in Figs. 3(b)~(e) are reexamined by introducing the volumetric efficiency of a pulse combustor, which is defined by the ratio of the total volume of fresh mixture and air supplied per cycle at NTP to the volume of the combustor, and is considered to make an overall assessment of the pulse

Fig. 6 Behavior of volumetric efficiency of pulse combustor with tailpipe geometry, $\phi_p=3.0$

combustor possible.

The volumetric efficiency, denoted by η_v , is expressed by

$$\eta_v = \frac{Q_{tN} \times 10^{-3}}{60 f_0 V} \quad (1)$$

where $Q_{tN}(=Q_{tN} + Q_{atN})$ [L/min] indicates the total fresh inflow, $V[\text{m}^3]$ the volume of the combustor, and $f_0[\text{Hz}]$ the pulsating frequency.

Figures 6(a) and (b) summarize the relations between the volumetric efficiency and the total fresh inflow for the tailpipe cross-sectional area of $A=5.0 \text{ cm}^2$ and 2.5 cm^2 , respectively, where the tailpipe length, L , is shown as a parameter. Data given in Fig. 6(a) correspond to those given in Figs. 3(b) and (c), and data in Fig. 6(b) to those in Figs. 3(d) and (e).

Figure 6 reveals the following four features with respect to the behavior of the volumetric efficiency. The first feature appears in the approximate amalgamation of the pulsating limits for each tailpipe geometry, independent of the rich and lean limits, into a single, straight line.

The second is given by the fact that the average variations of the volumetric efficiency with the total fresh inflow, which are indicated by straight lines in Fig. 6, depend strikingly on the tailpipe length, showing only a little dependency on the cross-sectional area. A gradient of the straight line is found, according to Eq.(1), to be inversely proportional to the pulsating frequency in the case of constant combustor volume. Thus, it may be considered that the above characteristic result means that the periodic ignition and combustion mechanisms are controlled mainly by the oscillation due to pipe resonance in the tailpipe, rather than that caused by Helmholtz-type resonance of the whole combustor system.

The third feature is such that the maximum volumetric efficiency attainable for the present pulse combustor is found to be no more than about 17% for the tailpipe geometry of $A/L=2.5/2.0$ suitable for the largest TDR. A low volumetric efficiency implies a low fresh inflow into the combustion chamber, resulting in a weak cooling effect. Thus, it may be expected that a comparatively high average temperature field is formed in the combustor. Temperature measurements in the previous paper, which reported the average temperature of $1300 \sim 1400^\circ\text{C}$ ⁽⁸⁾, give experimental evidence of the above speculation.

The third feature also suggests the existence of the upper critical limit of the volumetric efficiency. Forcing the secondary air into the present pulse combustor by the blower gives the maximum efficiency of 20%, where the blower has specifications of $15 \text{ m}^3/\text{min}$ and 1.6 kPa . This value is only about 3% larger than that obtained for the natural ventilation. The remarkable increase of CO emission due to an imperfect combustion should also be taken into account in the range of the high fuel flow rate. It may be concluded, therefore, that the naturally ventilated pulse combustor has the upper critical volumetric efficiency of about 17%.

The fourth feature concerns the lower limit of the volumetric efficiency, which may be provided by a nearly constant value of 4%, regardless of the tailpipe geometry. It is inferred, thus, that the minimum volumetric efficiency obtained proportionates to the minimum energy requirement appraised by Rayleigh's criterion⁽⁹⁾.

The third and fourth features are combined to give the critical pulsating limits in terms of the volumetric efficiency, after the regulation of the CO emission is made for an evaluation of the maximum

fuel flow rate. The use of the bracketed values in Table 1, then, lowers the upper critical volumetric efficiency to $(\eta_v)_{\max}=12\%$, while the lower remains unchanged, $(\eta_v)_{\min}=4\%$. Consequently, the practical, allowable range of the volumetric efficiency of the pulse combustor may be given as $\eta_v=4\sim12\%$.

It is worthwhile to refer, at this point, to the practical significance of the critical pulsating limits, because they are a useful guide in the pulse combustor design. The maximum heat-release rate, $q_{\max}[\text{MJ/h}]$, allowable for a given combustor volume, $V[\text{m}^3]$, which is one of the most important design parameters of the pulse combustor, is estimated by the expression,

$$q_{\max} = \frac{3600(\eta_v)_{\max} f_0 V \Delta H}{(1 + \mu_t \lambda_{th})} \quad (2)$$

where $f_0[\text{Hz}]$ indicates the pulsating frequency particular to a given geometrical configuration of the combustor, μ_t the overall air ratio ($=1/\phi_t$), λ_{th} the theoretical air-fuel ratio in volume, and $\Delta H[\text{MJ/m}^3]$ the heating value of fuel used. Equation (2) shows that the pulse combustor with a short tailpipe and a large volume is suitable for getting a high heat-release rate.

4. Concluding Remarks

In this paper, a practical method was experimentally examined to accomplish a wide-range and low-noise-level pulse combustor in the case of natural ventilation. The results are summarized as follows.

(1) A supply of a rich mixture, instead of pure fuel, which is outside the flammability limit and has an equivalence ratio of 3.0 in the present investigation, can attain a higher combustion intensity of 53.4 MW/m³ and a larger turn-down ratio of 4.5 than those attained by the usual pulse combustor by factors of about 1.6 and 2.0, respectively. The optimum equivalence ratio of a rich mixture, however, depends on the mixing process particular to each combustion system employed.

(2) Decreasing the tailpipe cross-sectional area from 5.0 cm² to 2.5 cm² reduces the noise level by about 5 dB(A). Also, a quiet pulse combustor with a noise level of 55~70 dB(A) is obtainable without any silencer by operating the present pulse combustor at a partial combustion load of 15~35%.

(3) The volumetric efficiency of a pulse combustor, which is defined by the ratio of the total fresh inflow per cycle at NTP to the combustor volume, is

found to be limited by the practical range of $\eta_v=4\sim12\%$. This enables an approximate evaluation of the maximum and minimum heat-release rates allowable for a given geometry of the pulse combustor.

(4) A higher heat-release rate can be successfully obtained by operating such a pulse combustor as one composed of a short tailpipe and a large combustion chamber.

References

- (1) Kellor, J.O., Saito, K. and Kishimoto, K., An Experimental Investigation of a Pulse Combustor (Flow Visualization by Schlieren Photography), Fall Meetings of the Western States Section of the Combustion Institute, No. 84-56 (1984).
- (2) Nakamoto, M., Hosaka, M., Inui, I. and Okamoto, K., Pulse Combustion Technology for Water Heater, National Technical Report, (in Japanese), Vol. 30, No. 5 (1984), p. 683.
- (3) Westbrook, C.K., Successive Reignition of Fuel-Air Mixtures and Pulse Combustion, Fall Meetings of the Western States Section of the Combustion Institute, No. 85-37 (1985).
- (4) Kellor, J.O., The Dynamics of Injection, Mixing and Combustion in a Valved Pulse Combustor, Fall Meetings of the Western States Section of the Combustion Institute, No. 85-38 (1985).
- (5) Saito, T., Saito, K., Hisaoka, S., Hirasawa, F., Tanaka, S. and Fujita, Y., An Experimental Study on the Pulse Combustor (Characteristics of the Pulse Combustion for Designing), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 51, No. 469, B (1985), p. 3068.
- (6) Saito, K., Kellor, J.O., Kishimoto, K. and Saito, T., An Experimental Study on the Heat Release Rate in the Pulse Combustor, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 52, No. 479, B (1986), p. 2722.
- (7) Kellor, J.O. and Westbrook, C.K., Response of a Pulse Combustor to Changes in Fuel Composition, Proc. of 21th Int. Symp. Comb., (1986), in printing.
- (8) Ohiwa, N., Yamaguchi, S., Hasegawa, T., Qin, Bo Kui and Okada, A., An Experimental Study of the Ignition and Combustion Mechanisms in a Pulse Combustor (Combustion Characteristics Supplied with a Propane-Air Mixture), Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 52, No. 476, B (1986), p. 1913.
- (9) Strehlow, R.A., Fundamentals of Combustion, (1968), p. 274, International Textbook Company.