Experimental Study on High Loading Combustor for Lift Jet Engine

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This paper deals with the parameters to specify a performance of a spray-type combustor which is a high loading combustor for a lift jet engine. The mixing parameter to control a combustion efficiency was obtained analytically by means of simplifying a primary zone, and its effectiveness was confirmed experimentally. The combustor geometry used for the test was 90-deg sector model of an annular type, the 42 combinations of different seven swirlers and six deflectors were tested systematically. The maximum combustion loading of 2.0 x 10^7 Btu/hr/cu ft combustion volume per atmosphere was obtained.


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NOMENCLATURE

\( A_{DI} \) = inner diffuser inlet area, sq ft
\( A_{DO} \) = outer diffuser inlet area, sq ft
\( A_L \) = combustion liner sectional area, sq ft
\( A_s \) = deflector inlet area, sq ft
\( A_{t} \) = combustor inlet area = \( A_{DI} + A_s + A_{DO} \), sq ft
\( A_R \) = reference sectional combustor area, sq ft
\( a \) = constant
\( C_{DW} \) = correlation parameter, lb/ft\(^2\)
\( C_p \) = specific heat at constant pressure, Btu/(lb-deg R)
\( D \) = combustion liner width, ft
\( D_{a} \) = Damköhler number
\( D_{a}^* \) = modified Damköhler number
\( d_h \) = swirler hub diameter, ft
\( d_s \) = effective swirler diameter = \( \sqrt{dt^2-dh^2} \), ft
\( dt \) = swirler tip diameter, ft
\( G_a \) = angular momentum flux, lb-ft
\( G_x \) = axial momentum flux, lb
\( g \) = acceleration due to gravity, fps
\( H_u \) = lower calorific value, Btu/lb
\( h \) = deflector inlet width, ft
\( K_1, K_2 \) = constant
\( L \) = combustion liner length, ft
\( P \) = pressure, lb/sq ft
\( P_{IN} \) = inlet total pressure lb/sq ft
\( P_{DW} \) = deflector wall pressure lb/sq ft
\( Re \) = Reynolds number
\( S \) = swirl number
\( T \) = temperature, deg R
\( V \) = velocity in combustor, fps
\( W_a \) = total airflow rate, lb/sec
\( W_f \) = fuel flow rate, lb/sec
\( W_{h,w} \) = primary airflow rate through liner holes, lb/sec
\( W_i \) = entrainment airflow rate, lb/sec
\( W_s \) = airflow rate through swirler, lb/sec
\( X \) = airflow rate through swirler, lb/sec

Greek Symbols

\( \alpha \) = constant
\( \beta \) = mixing parameter
\( \gamma \) = jet density, lb/cu ft
\( \bar{\gamma} \) = average gas density, lb/cu ft
\( \delta \) = exit air angle of swirler, deg
\( \eta \) = combustion efficiency
\( \mu \) = fuel-air ratio
\( \phi \) = combustion efficiency correlating parameter = \( \frac{\Pi_{75AR}}{0.75 \exp(T/300)}, \frac{W_a}{lb^{.75}-sec/lb\cdot ft^{0.75}} \)
\( T_B \) = average reaction time, sec
\( T_D \) = physical ignition delay time, sec
\( T_M \) = average mixing time, sec
\( T_R \) = average residence time, sec
\( \phi \) = equivalence ratio

Subscripts

\( a \) = air
\( M \) = mixing
\( p \) = primary zone
\( st \) = stoichiometric
1 INTRODUCTION

One of the most important requirements for a lift jet engine design is to reduce an engine weight, and a combustor must be also lightweight and compact, what is called a high loading combustor.

Recently, combustion chambers are being designed with an analytical method. From the work by LeFebvre, (1) a typical diameter and a sectional area of a combustor can be obtained by the combustion efficiency correlating parameter, \( \phi \).

Unfortunately, however, in case of the smaller \( \phi \), which means a high loading combustor, the quantitative analysis cannot be available with an accuracy. These typical diameters and sectional areas are not sufficient for factors to specify the performance of a combustion chamber.

So, it is necessary to analyze further the flow pattern and the mixing of air and fuel in a combustion zone in case of high loading combustor design.

The analysis should be different in each combustion chamber type, since flow pattern and mixing depend on chamber geometry and fuel-injection system.

From this viewpoint, this work will be mainly concerned with the most typical type for recent aircraft gas turbines which is a straight-through annular type with swirlers. The fuel is injected by swirl atomizers.

This paper has two purposes. One purpose is to obtain the general parameters analytically which are more effective at the design of a high loading combustor. The second is to confirm the effectiveness of the parameters experimentally.

2 ANALYSIS ON PARAMETERS CONTROLLING COMBUSTION PERFORMANCE

Modified Damköhler Number

The main combustion processes in a primary zone of a fuel spray type combustor are fuel evaporation, fuel-air mixing, ignition, chemical reaction, etc.

It is difficult to analyze on combustion chambers strictly, because these processes occurred side by side in a complicated flow pattern of a primary zone. Therefore, in order to obtain parameters controlling the combustion performance, it is better to discuss with the simple model

1 Numbers in parentheses designate References at end of paper.

substituted for the combustor to be analyzed.

In this paper, the following assumptions are taken to simplify the model.

1 The combustion processes are almost accomplished in the primary zone, the parameters controlling the combustion processes of the primary zone can be signified the whole combustion performance.

2 The flow in the primary zone has uniform fuel-air mixing distribution which is calculated from the average values of the primary zone.

3 The representative combustion processes might be the physical ignition delay and the chemical reaction, and those processes occur in series.

Now, before the analysis on the actual combustor is taken, we must consider obtaining non-dimensional parameters affecting the combustion efficiency.

Bragg (2) reported on the parameters that control combustion performances — two dimensional parameters, Reynolds number, Damköhler (2) number, and the reaction rate for a simple model, such as a one-dimensional and pre-mixed combustor with a constant area.

The reaction rate specifies the chemical combustion process and is affected by the inlet air pressure, temperature, and contents of fuel-air ratio, \( \phi \).

After all, one can also consider Reynolds number, Re, Damköhler number, \( Da \), the inlet air pressure, \( P \), temperature, \( T \), and equivalence ratio, \( \phi \), for the parameters controlling the combustion performance.

In these parameters, Reynolds number can be ignored in case of a high loading combustor which has larger Re, since a combustion efficiency is almost not affected at the larger Reynolds number, which is greater than \( 10^{5} \) (4).

The parameters, \( P \) and \( T \), are given by engine specifications generally, combustor designers cannot select arbitrarily.

Hence, the most important parameters at designing combustors are Damköhler number and the equivalence ratio.

These parameters, however, are not effective for an actual combustor, because the most important parameters on physical ignition delay processes, especially mixing process, are not considered.

In order to include the physical ignition delay processes, the modified Damköhler number, \( Da \), shall be proposed using the reaction time, \( T_{B} \), and the physical ignition delay time, \( T_{D} \), in-
instead of the only reaction time, $\tau_B$.

$$D' = \frac{\tau_R}{\tau_B + \tau_D} \quad (1)$$

The combustor designed so that the fuel-air ratio in the primary zone is near to the stoichiometric, since it is important to get a heat release in the primary zone as highly as possible, especially on high loading combustors.

In such a case, the physical ignition delay time, $\tau_D$, is more important rather than the reaction time, $\tau_B$; equation (1) might be modified by

$$D' = \frac{\tau_R}{\tau_D} \quad (1')$$

The modified Damköhler number may be better for the actual combustion chamber.

**Mixing Parameter**

The two most important parameters, $D'$ and $\phi$, to control the combustion efficiency have been proposed in the foregoing section. The next problem is to calculate actually these parameters at the design of combustors.

The residence time in the combustor and the physical ignition delay time are necessary to calculate the modified Damköhler number, and, in the equivalence ratio, the fuel-air ratio distribution in the combustion chamber is necessary.

The flow pattern presented here is simplified by the following assumptions in order to calculate $D'$ and $\phi$.

1. Main flows in the primary zone consisted of the jet flow from each swirler and the reverse flow which is formed near the swirler axis behind it.
2. The flow pattern of a primary zone depends almost on swirling jet and airflow rate through swirlers.
3. The fuel and air mixing rate is increased in proportion to the entrainment airflow rate to the swirling jet. The entrainment airflow rate depends on the swirling jet flow pattern.
4. The axial length of the primary zone is defined as the distance from the swirler exit to the rear stagnation point of the recirculation zone.
5. The mixing of fuel and air specifies the physical ignition delay time, and $\tau_D$ in equation (1) is able to be a mixing time, $\tau_M$.

**Fig. 1 Schematic flow pattern of a primary zone with notations; only half-plane is shown. 1 flow deflector; 2 fuel nozzle; 3 swirler; 4 mixing zone; 5 liner air hole; 6 rear stagnation point; 7 contour of recirculation flow**

The simplified schematic flow pattern in a primary zone is shown in Fig. 1 with notations. The average fuel-air ratio of the primary zone may be described by

$$\phi_p = \frac{W_f}{W_A + W_{W_f}} \quad (2)$$

Here, $W_h, W$ means an effective airflow rate through first air holes of a combustion liner into the primary zone, but it is difficult to calculate quantitatively. Assuming the airflow rate of the primary zone is defined by the airflow through swirlers and the entrainment airflow, it might be given by the airflow rate through swirlers only, from assumption 3. Hence, the equivalence ratio of the primary zone may be written by

$$\phi = \frac{(W_f/W_s)}{\mu_{st}} \quad (3)$$

In the modified Damköhler number, the calculating procedure is described in the following.

Assuming that the necessary length, $L_M$, to mix completely is proportional to $L_p$, and the mixing flow rate, $W_M$, is proportional to $W_i$ from assumption 3, the average mixing time, $\tau_M$, may be expressed as equation (4)
On the other hand, it would be better to take a volume, except the recirculation zone, when the average residence time, $\tau_R$, is calculated. If the effective area might be defined to be proportional to the swirler exit annular area, the residence time, $\tau_R$, can be written by equation (5), since the airflow rate in the primary zone depends on the airflow through swirlers, $W_s$, and the entrainment flow, $W_i$.

$$\frac{T}{\tau} \propto \frac{\tau^2}{W_i}$$  \hspace{1cm} (4)$$

The entrainment flow rate in equation (4) is obtainable by modifying the entrainment flow in a static air from reference (2).

The entrainment flow rate into the swirling jet, $dW_i/dx$, is expressed in equation (6) from reference (5).

$$\frac{dW_i}{dx} = k_i \sqrt{G_x} \left( \frac{G_x d_s}{G_a} \right)^\alpha$$  \hspace{1cm} (5)$$

This is obtained by a dimensional analysis, assuming that the entrainment airflow is defined by the axial momentum flux, the angular momentum flux, the effective swirler diameter, and the jet density.

The converse of the last term in equation (6), $G_a/(G_x d_s)$, is called by swirl number; it is decided by a swirler boss ratio, $\nu$, and air exit angle, $\delta$.

$$S = \frac{G_a}{G_x d_s} = \frac{\tan \delta}{3} \left( \frac{1 - \nu^2}{1 - \nu^2} \right)^{1/2}$$  \hspace{1cm} (6)$$

The axial momentum flux, $G_x$, is written with $W_s$, $d_s$, $\gamma$ by

$$G_x = \frac{4 W_s^2}{\pi d_s^2 \gamma}$$  \hspace{1cm} (7)$$

Substituting equations (7) and (8) into equation (6),

$$\frac{dW_i}{dx} = k_i \frac{W_s}{d_s} S^\alpha$$  \hspace{1cm} (8)$$

Here,

$$\alpha = \frac{1}{2}, \quad K = \text{const.}$$

From reference (5), in the case of a jet into a static field, $\alpha = 1$. The rear stagnation point of recirculation zone, which defines the primary zone length, $L_p$, might depend on an inner diameter in case of a simple bluff body (6). As a swirl angle is usually adopted around 45 deg, this work takes it constant, and the length, $L_p$, is assumed to be proportional to the inner diameter of the swirler.

Integrating equation (9) from the foregoing assumption,

$$\frac{W_i}{W_s} \propto S^{\alpha} \left( \frac{d_h}{d_s} \right)$$  \hspace{1cm} (9)$$

Hence, the modified Damköhler number can be written from equations (1), (4), (5), and (10).

$$D'_{a} = \frac{T}{\tau} \propto \frac{\nu}{\nu_{e}} \left( \frac{d_h}{D} \right) \left( \frac{d_l}{D} \right) S^\alpha$$  \hspace{1cm} (10)$$

Now, the mixing parameter is defined as the following.

$$\beta = \left( \frac{d_h}{D} \right) \left( \frac{d_l}{D} \right) S^\alpha$$  \hspace{1cm} (11)$$

This parameter is calculable from swirler geometry and combustion liner dimension if $\alpha$ is decided.

The correlation between these parameters and a combustion efficiency is explained in Fig. 2 schematically. It shows that a combustion efficiency is increased if a high mixing parameter is taken, and that the equivalence ratio should
1. Combustor for test
2. Fuel filter
3. Fuel flow control valve
4. Fuel by-pass valve
5. Fuel flow meter
6. Air flow control valve
7. Air flow meter
8. Compressor
9. Electric motor
10. Fuel pump

Fig. 3 Schematic diagram of air and fuel flow system

1. Air flow reflector
2. Collector of air flow through Swirlers
3. Combustion liner
4. Fuel atomizer
5. Swirler
6. Fuel manifold
7. Air bleed pipe
8. Outer casing
9. Inner casing
10. Window glass

\[ A_R = 0.4725 \text{ ft}^2 \]

Fig. 4 Test combustor with main dimensions
be nearly stoichiometric. This quantitative
correlation, however, should be obtained by ex-
periments, and it will be expressed in the follow-
ing.

3 EXPERIMENT

Experimental Apparatus

The schematic diagram on the airflow and
the fuel flow system is shown in Fig. 3. The
part within a dotted line of the upper left hand
in Fig. 3 shows an air bleed pipe which is es-
specially set in order to measure the flow rate
into a combustion liner only through swirlers
without combustion. It was not used after getting
the correlation curve between the airflow rate
through swirlers and the inlet air deflector's
wall pressure.

The test combustor is shown in Fig. 4 with
main dimensions, and its photograph is Fig. 5.

The combustion chamber geometry was a 90-deg
sector model of an annular type. The three fuel
atomizers were used to supply fuel, and the three
swirlers were installed on the liner front wall
coaxially with the fuel atomizers.

The collector box, shown with a dotted chair
line in Fig. 4, was only used to measure the flow
rate through swirlers. The photograph of the
bleed air pipe connected with the collector box
is shown in Fig. 6.

The combustion chamber consisted of the
inlet air deflector, the swirlers, the combustion
liner, and the fuel nozzles. They were assembled
with bolts, in order to get various combinations
easily.

Design Specification

The specification of the combustion chamber
at the design point was decided as shown in Table
1, according to the specification for an engine
for VTOL aircraft. So, the combustion loading
is very high, while the pressure loss is rather
high compared to propulsion engines. It is due
to taking the high reference sectional velocity
to get the high loading.

The combustion liner design data is shown
in Table 2. These values were constant through
this test.

The six inlet air deflectors were made. As
shown in Table 3, they had different inlet areas
respectively in order to investigate the effects
of the primary equivalence ratio, \( \phi_p \), which de-

pends on the airflow rate through swirlers. As
was known from Section 2, the mixing parameter
is decided mainly from the swirler geometrical
dimensions.

So, the dimensions of swirlers were selected

<table>
<thead>
<tr>
<th>Table 1: Values at Design Point</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air-Fuel Ratio</strong></td>
</tr>
<tr>
<td><strong>Reference Velocity</strong></td>
</tr>
<tr>
<td><strong>Combustion Efficiency</strong></td>
</tr>
<tr>
<td><strong>Pressure Drop</strong></td>
</tr>
<tr>
<td><strong>Temperature Rise</strong></td>
</tr>
<tr>
<td><strong>Combustion Loading</strong></td>
</tr>
</tbody>
</table>
Table 2 Combustion Liner Design Data

<table>
<thead>
<tr>
<th>Air Hole Area-Inner (AHI)</th>
<th>Air Hole Area-Outer (AHO)</th>
<th>Total Hole Area (AHT)</th>
<th>AHI/AHO</th>
<th>AHI/AR</th>
<th>Liner Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.92 in²</td>
<td>12.05 in²</td>
<td>20.97 in²</td>
<td>0.727</td>
<td>0.225</td>
<td>0.225 ft³</td>
</tr>
</tbody>
</table>

Table 3 Airflow Deflector Design Data

<table>
<thead>
<tr>
<th>Slit Width</th>
<th>Inlet Slit Area (As)</th>
<th>Inlet Area (Aa)</th>
<th>As/Aa</th>
<th>At/Aa</th>
<th>Ann/Aa</th>
<th>Ann/Aa</th>
</tr>
</thead>
<tbody>
<tr>
<td>VS 15</td>
<td>0.050 in</td>
<td>0.800 in²</td>
<td>0.063</td>
<td>0.123</td>
<td>0.042</td>
<td>0.042</td>
</tr>
<tr>
<td>VS 22</td>
<td>0.060 in</td>
<td>0.840 in²</td>
<td>0.031</td>
<td>0.061</td>
<td>0.023</td>
<td>0.023</td>
</tr>
<tr>
<td>VS 45</td>
<td>0.110 in</td>
<td>1.220 in²</td>
<td>0.008</td>
<td>0.018</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>VS 85</td>
<td>0.150 in</td>
<td>1.520 in²</td>
<td>0.018</td>
<td>0.036</td>
<td>0.006</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Table 4 Swirler Design Data

<table>
<thead>
<tr>
<th>Boss Ratio</th>
<th>Effective Diameter</th>
<th>Vane Diameter Outer-Inner</th>
<th>Vane Diameter Throat</th>
<th>Solidity at Mean Vane Diameter</th>
<th>At/Aa</th>
<th>Vane Stagger Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.750 in</td>
<td>2.72-2.05 in²</td>
<td>1.58 in²</td>
<td>0.27</td>
<td>0.273</td>
<td>45 degree</td>
</tr>
<tr>
<td>S2</td>
<td>0.512 in</td>
<td>2.72-2.21 in²</td>
<td>1.39 in²</td>
<td>1.07</td>
<td>0.057</td>
<td>45</td>
</tr>
<tr>
<td>S3</td>
<td>0.755 in</td>
<td>2.45-1.81 in²</td>
<td>1.27 in²</td>
<td>1.66</td>
<td>0.056</td>
<td>45</td>
</tr>
<tr>
<td>S4</td>
<td>0.702 in</td>
<td>2.50-2.05 in²</td>
<td>1.27 in²</td>
<td>1.07</td>
<td>0.056</td>
<td>45</td>
</tr>
<tr>
<td>S5</td>
<td>0.771 in</td>
<td>2.55-1.85 in²</td>
<td>1.27 in²</td>
<td>1.13</td>
<td>0.056</td>
<td>45</td>
</tr>
<tr>
<td>S6</td>
<td>0.503 in</td>
<td>2.02-1.31 in²</td>
<td>1.277 in²</td>
<td>1.16</td>
<td>0.056</td>
<td>45</td>
</tr>
<tr>
<td>S7</td>
<td>0.710 in</td>
<td>1.973 in²</td>
<td>1.72 in²</td>
<td>1.13</td>
<td>0.082</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 5 Mixing Parameter β for Each Swirler

<table>
<thead>
<tr>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.126</td>
<td>0.140</td>
<td>0.0987</td>
<td>0.123</td>
<td>0.125</td>
<td>0.107</td>
<td>0.116</td>
</tr>
</tbody>
</table>
The stagger vane angle was 45 deg constant, because of being adopted mostly around 45-deg swirler in the actual combustors for the recent aircraft engines. The values of seven swirlers are shown in Table 4. The photograph of the combustion chamber assembly, except the inlet air deflector, is shown in Fig. 7.

The six deflectors are shown in Fig. 8.

Experimental Procedure

Measurement of Airflow Rate through Swirlers. Since it was predicted that a method of a direct measurement of the airflow rate through swirlers, was, for instance, by pitot tube installed in the deflector would not be accurate, it was preferred to measure indirectly by the correlation parameter, $C_{DW}$, that was obtained from deflector's wall pressures etc. from equation (13).

The actual airflow rate through swirlers was measured by the flow meter which was installed on the bleed tube.

The pressure taps were located on the deflector's wall as shown in Fig. 9. The correlation parameter, $C_{DW}$, is obtained by the air density, $\gamma_a$, the inlet air total pressure, $P_{IN}$, and the average deflector's wall pressure, $P_{DW}$.

$$C_{DW} = \sqrt{\frac{\gamma_a}{\pi} \frac{P_{IN}}{P_{DW}}}$$ (13)

The actual airflow rate through swirlers could be obtained from the correlation curve and $C_{DW}$, without the bleed tube. The tests for obtaining the correlation curves were carried on each deflector with the various swirlers to change total airflow rate.

Combustion Tests. The inlet air pressure, $P_{IN}$, was set around atmospheric, and the temperature was about 195 F.

The reference sectional air velocity was 118 fps constant, and the fuel flow rate was changed so that the fuel-air ratio was changed.

The inlet and outlet temperatures and deflector's wall pressures were measured by thermocouples and manometers, respectively, at static combustion condition. The outlet temperatures were measured by four thermocouples which had the four different radius points each.

The 42 combinations of different seven swirlers and six deflectors were tested with combustion.
Experimental Results

Airflow Rate through Swirlers. The correlation curves for all deflectors are shown in Fig. 10, which indicated the airflow rate through swirlers versus the correction parameter, $C_{pM}$. Measuring points are also plotted for some deflectors, VS30, VS50, VS65.

It is noticed that there is almost no difference between the swirler dimensions.

The swirler airflow rate for the actual combustion chamber removed by the bleed tube are plotted in Fig. 11, obtained by using the correlation curves of Fig. 10 and the correlation parameter, $C_{pM}$.

The swirler airflow rate was increased when the deflector inlet area was increased, except for the smaller deflectors, VS15 and VS22.

The effect of swirler dimensions to the airflow rate was slightly found in the greater deflector inlet area.

Combustion Efficiency for the Various Combinations. The combustion efficiency is calculated by the following equation from the inlet air temperature and the exit average temperature.

\[ \eta = \frac{(W_d + W_f)(C_T)_{in} - W_d(C_T)_{out}}{H_f W_f} \]  

The combustion efficiency for each swirler was changed about 10 percent for various deflectors as shown in Fig. 12. The efficiency for the deflector VS30 was much better through all combinations.

When the deflector inlet area was increased, the efficiency was likely to be decreased in the leaner mixture region. On the contrary, in case of narrower deflector's inlet area, the same was in the richer mixture region.

The best combination looks to be S2-VS30 shown in Fig. 12, and the maximum combustion loading of $2.0 \times 10^7$ Btu/hr/ft of combustion volume per atmosphere was obtained with this combination. These efficiency curves are re-plotted with the primary equivalence ratio which is calculated from the swirler airflow rate and the fuel flow rate in Fig. 13 for each swirler.

It is noticed that only one curve is able to be drawn in spite of the different deflectors for each swirler, even though the data are scattered.

The peak efficiency is at a larger equivalence ratio than stoichiometric for each swirler. The airflow considered in this analysis is only the swirler airflow except the reverse airflow in the primary zone.

It might be considered that the equivalence ratio near the peak efficiency of each curve is the average stoichiometric ratio of the primary zone.

All curves in Fig. 13 are rewritten correctly in Fig. 14 in order that the characteristics of the swirlers are comparable. An operat-
Fig. 12 Combustion efficiency versus total air-fuel ratio for various swirlers
Fig. 13 Combustion efficiency versus equivalence ratio of primary zone for various swirlers.
Discussions Correlating with Mixing Parameter, $\beta$, and Combustion Efficiency. The mixing parameter, $\beta$, for each swirler is indicated in Table 5 when $a$ equals 1.

The maximum $\beta$ is 0.140 for the swirler, S2, and the minimum is 0.0987 for the swirler, S3. It can be generally said that the efficiency is better for the larger $\beta$ from Fig. 15.

The two methods are taken to correlate between $\beta$ and the combustion efficiency, since each combustion efficiency curve is not similar, crossing each other, and the peak efficiencies are not necessarily on the same equivalence ratio as expected in Section 2 and as shown in Fig. 2.

One is to take the peak efficiency as the efficiency. The other is to take the average efficiency for an appropriate equivalence region which is included in the performance on an operating region. These are shown in Fig. 15. From this figure, it is much better to take the average efficiency than the peak efficiency.

4 CONCLUSIONS

The parameters which control the combustion efficiency on a high loading combustor with swirlers were obtained theoretically by means of simplifying the primary zone, and those effectiveness were confirmed experimentally also.

1 These parameters are the average equivalence ratio of a primary zone and the modified Damköhler number.

2 The Damköhler number could be substituted by the mixing parameter, $\beta$, which is indicated by the ratio of a residence time and a mixing time in a primary zone.

3 The average equivalence ratio in a primary zone, which was calculated from the overall fuel flow rate and the airflow rate through swirlers, could have a good correlation with a combustion efficiency.

4 The airflow rate through swirlers was obtained from the correlation curves which had been measured by the bleed tube system before the combustion tests.

5 The peak efficiency was not at the stoichiometric equivalence ratio which was based only on the airflow from swirlers. This means that it is not better to inject the airflow which is necessary to burn completely from swirlers only.

6 The higher combustion efficiency was obtained for the higher mixing parameter, $\beta$, as estimated from theoretical analysis in this work.

7 It is better to take the average efficiency than the peak efficiency to correlate with $\beta$.

8 The maximum combustion loading of $2.0 \times 10^7$ Btu/h/cu ft combustion volume per atmosphere was obtained.
REFERENCES


