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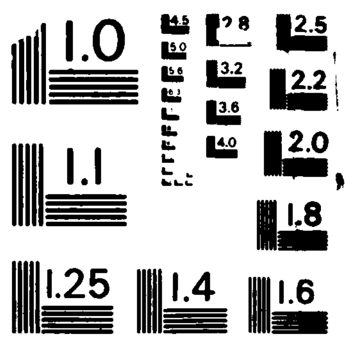

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AN APPROACH OF PREVENTING COMBUSTION VIBRATIONS OF ROCKET ENGINE WITH LATERAL BAFFLE

by

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An Approach of Preventing Combustion Vibrations of Rocket Engine With Lateral Baffle /72

Di Lianshun and Xing Fuyuan

Abstract

In the process of developing the variable thrust rocket engine, combustion vibrations are encountered in the low end of the operating conditions. We used a lateral baffle to satisfactorily solve the problem.

This paper mainly introduces the experimental results and qualitative analysis. The approach is novel. It can be used as a reference.

I. Introduction

As the development work proceeded, when the variable thrust rocket engine operated at three fifths of the specified full thrust, the pressure in the combustion chamber caused violent vibrations. In order to solve this problem, we designed a lateral baffle to be placed in the combustion chamber in early 1983. The results of several warm tests showed that the use of the lateral baffle to suppress combustion vibration is relatively effective.

*Manuscript received on September 10, 1984

II. Basic Operating Principle of the Variable Thrust Rocket Engine

(1) Composition of the Engine

As shown in Figure 1, the engine comprises the following basic components

1 - fuel tank

2 - oxidant tank

3 - injector

4 - thrust chamber

5 - inlet electromagnetic valve

6 - outlet electromagnetic valve

7 - combustion-chamber feedback pressure transducer

8 - variable thrust controller

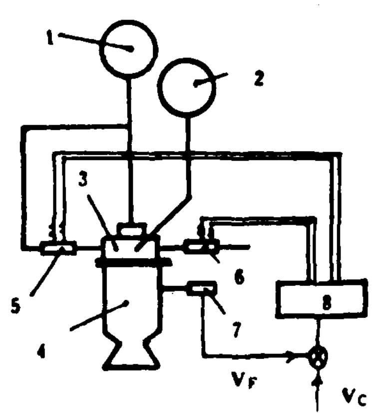

Figure 1. Schematic Diagram of the Operating Principle of the Variable Thrust Rocket Engine

(2) Operating Principle of the Variable Thrust Engine

The thrust of the engine is varied by the variable thrust controller.

When thrust is to be increased, it is necessary to raise the /73
control voltage V_c. The instant that V_c is raised, a voltage drop between V_c and the negative feedback voltage V_f of the combustion-chamber pressure transducer is created:

$$\Delta V = V_c + V_f$$

When ΔV is positive, the variable thrust controller operates the inlet electromagnetic valve on the injector to lift the needle valve. This effectively increases the injection cross-section area and raises the injection flow rate of the propellant. The pressure of the combustion chamber is increased to raise the thrust of the engine.

Because the combustion-chamber temperature is increased, the absolute value of the feedback voltage V_f is also increased, causing the value of ΔV to drop. When $\Delta V=0$, the inlet valve stops working and the needle valve is stabilized at the new position. Then, the engine operates at the high thrust state.

It is the opposite process when the thrust is reduced. The control voltage V_c is lowered to make ΔV negative. In this case, the outlet valve is activated. The needle valve opening is reduced to cut down the flow. The net result is that the thrust is decreased. The absolute value of the feedback voltage decreases. When $\Delta V=0$, the engine operates at a low thrust state.

III. Combustion Pulsation of Variable Thrust Rocket Engine At Low Operating Mode

Combustion pulsation frequently appeared in testing the variable thrust rocket engine during the development process. The recording curve is shown in Figure 2. This combustion pulsation is usually occurring throughout the entire period under a specific operating condition. In some cases, the amplitude is less. In other cases, the amplitude is large.

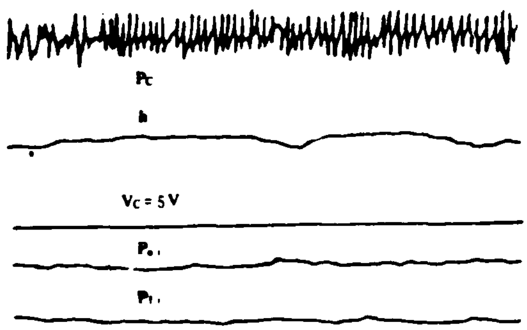

Figure 2. Recording of the Combustion Chamber Pressure Pulsation

Since the oxidant nozzle is enlarged, this combustion pulsation effect basically does not exist anymore. Nevertheless, a violent combustion vibration is observed. This type of vibration always occurs when the control voltage is at V_C=3V. Furthermore, it does not happen continuously in this operating condition. Instead, it is intermittent. This type of combustion vibration is shown in Figure 3.

Where p_c - combustion chamber pressure

h - injector needle valve opening

V_c - control voltage

p_{oi} - oxidant inlet pressure

p_{fi} - full inlet pressure

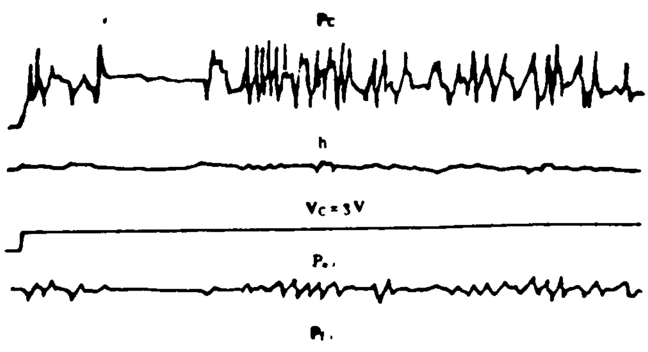

Figure 3. Recording of Continuous Combustion Vibrations at $V_c = 3V$

The special features of this type of violent intermittent vibrations are:

1. large amplitude; usually ranging from 60% to 200% of the main pressure;

2. no fixed frequency;

3. intermittent vibrations which do not appear throughout the entire process; and

4. delivery system pressure also fluctuates when the combustion-chamber pressure vibrates. Furthermore, the system pressure vibration is lagging behind the chamber-pressure oscillation by a fixed phase. However, based on Figure 2 we see that the effect on the system pressure is small during combustion pulsation.

From Figure 3 we can see that the phase of the chamber pressure is in front of the phase of the needle valve displacement and the phase of the pressure pulse of the delivery system. Therefore, we can conclude that the vibration of the combustion-chamber pressure causes the pulsation of the needle valve opening h and the delivery pressures p_{oi} and p_{fi}. The pulsation of h, p_{oi}, and p_{fi} is passive and the oscillation of the chamber pressure p_c is active. /74

It is our analysis that the pressure oscillation in the combustion chamber is an inevitable phenomenon. This is determined by the structure of the engine. The nozzle we are using is in the shape of a ring. Moreover, there are discrepancies in machining, cleanliness and concentricity. Therefore, the quality of the atomized jet and the homogenuity of the flow are less than ideal. These factors must have some effect on the stability of combustion. On the other hand, the combustion chamber we used is limited by the technical specifications. Its length is relatively short. Therefore, the propellant stays only for a short duration in the combustion chamber. Furthermore, in order to improve propellant mixing, a ring of a certain height was designed to be placed outside the ring nozzle. This measure increases the axial velocity of the jet.

In addition, there is another important factor which is the maximum thrust designed for the variable thrust liquid rocket engine. At lower thrusts, it operates out of its designed state, which definitely affects its operation.

We can conclude from the above analysis that it is inevitable for the combustion-chamber pressure of the engine to vibrate somewhat under different operating conditions. This conclusion has been experimentally verified. The combustion-chamber pressure curves obtained without the use of a baffle are all somewhat ragged.

As for the inhomogeneous atomization and mixing caused by all factors analyzed above which eventually cause the combustion flame to be non-uniform, this was proved by the following phenomena observed in the experiment:

1. We used a high silica-phenolic resin combustion chamber in each experiment. After disecting the chamber following the test, in most cases, the wall was found to melt unevenly. In the same cross-section, the amount burnt away varies circumferentially which indicates that the flame field in the combustion chamber is non-uniform. Along the axial direction, however, the chamber wall is burnt more near the inlet of the nozzle. This suggests that the combustion flame zone is near the nozzle inlet, which is relatively in the rear.

2. We conducted an investigation on the throat regeneration cooling scheme and performed an experimental study. The

experimental results showed that it was burned through in most cases 2 to 3 cm from the inlet of the converging section of the nozzle. The penetrated edge is clean cut and the surrounding metal shows no sign of overheating. This phenomenon can interpret the unevenness of the flame.

3. A lateral baffle is placed in the combustion chamber. The material used is also a high silica-phenolic resin. After testing, it was observed that the front end of the baffle showed serious local erosion; i.e., a local washing effect. This effect fully demonstrated that the combustion flame is non-uniform across the cross-section in the combustion chamber due to the inhomogenuity of injection, atomization and mixing. There are local intense flamejets in the combustion chamber. In addition, it also explains the function of the lateral baffle in the combustion chamber and its mechanism.

In conclusion, when there is no lateral baffle, there is always a pressure oscillation in the combustion chamber. This is an inevitable phenomenon. Nevertheless, it is within a tolerable range in most cases. The amplitude is not very large. In other words, it is within the range that the voltage of the control valve cannot effectively regulate. The combustion-chamber pressure curve is coarse. If affected by some incidental factors, sufficient energy may be released to cause the pressure of the combustion chamber to rise abruptly. Once the control potential difference ΔV exceeds the insensitive range of the electromagnetic valve, the outlet valve is activated to reduce the opening of the needle valve to cut down the flow. The pressure in the combustion chamber thus drops. Due to overcompensation, the inlet valve is activated by the feedback mechanism which raises the needle valve to increase the flow. Then, the combustion-chamber pressure is on the rise again. Consequently, the combustion-chamber pressure is being sent into oscillation at a relatively large amplitude. However, because the system is stable, this pressure oscillation will finally reach a stable value until a second pressure oscillation is created by the second energy release peak.

Why does the chamber-pressure oscillation occur when the control voltage V_C is around 3V? This is because the combustion efficiency changes abruptly under this operating condition. It is undergoing a transition from a high efficiency operating mode to a low combustion efficiency operating mode. In this transition period, although it burns at a lower efficiency, high efficiency combustion may occasionally happen, which instantaneously raises the combustion chamber pressure.

The abrupt changes in the combustion efficiency can be illustrated by the following list of measured data points: /75

V_c	1.085	2.010	3.023	5.034	3.024	2.008	1.085
p_c	4.043	6.173	7.083	9.833	8.024	5.983	4.113
α	0.469	0.483	0.438	0.542	0.450	0.470	0.344
φ_c	0.734	0.779	0.813	0.872	0.871	0.793	

Where a - residual oxygen index

ϕ_C - combustion efficiency

Because the mean energy release efficiency changes abruptly in the range V_C=3V~4V, and it is on the verge of low combustion efficiency when V_C is around 3V, it creates the condition necessary for energy release peaks to appear. The probability of pressure peak is the highest. This effect may be related to the fact that we used HNO_3 + N_2O_4/UDMH as the propellant, because the phase change of HNO_3 involves a long time factor.

IV. An Attempt to Add a Lateral Baffle in the Combustion Chamber

The addition of a lateral baffle is based on the following:

1. It can promote the thorough mixing of all the constituents of the propellant to achieve the homogeneous release of its energy in order to eliminate the root of vibration.

2. It lengthens the duration over which the propellant components stay in the combustion chamber to allow the combustion process to be completed more thoroughly.

3. It enhances the combustion gas disturbance behind the baffle in the combustion chamber to further mix the gas in order to achieve a perfect combustion process.

In view of these three points, we added a lateral baffle in the combustion chamber. The experimental results obtained before and after the baffle was added are described below:

a. The front end of the baffle was severely burned unevenly (as described earlier). However, the back side was evenly burned. This shows that the jet spray and the combustion gas are still non-uniform although the mist from the nozzle is repeatedly reflected by the ring and the center rod. After colliding with the lateral baffle, it is further mixed.

b. The precipitation of SiO_2 is serious on the back of the baffle, which indicates that the combustion is intense in this re-circulation zone. The mixing is even more complete after being enhanced by the disturbance caused by the circulation. The combustion flame zone, which is originally near the rear, is moved forward to the back of the baffle.

We conducted several experiments after adding a lateral baffle in the combustion chamber. The results indicate that the combustion is more stable. Figure 4 shows the recorded curves.

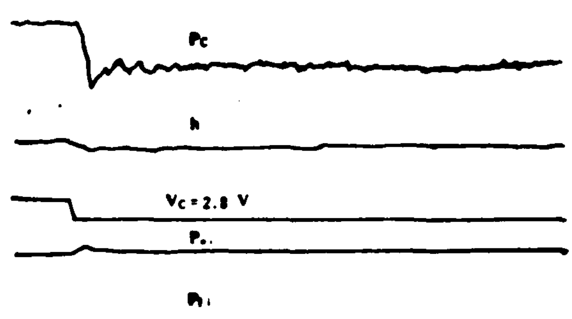

Figure 4. Experimental Recording With Baffle

Based on the above analysis and experimental proof, we realized that although a baffle could be used to suppress vibration, however, its optimal location is also a subject worthwhile some investigation. This problem will be analyzed in Section VII.

V. Problems Associated With Adding a Baffle in the Combustion Chamber

It is apparent that the combustion vibration of a variable thrust rocket engine at V_c=3V can be effectively suppressed by adding a lateral baffle in the combustion chamber. However, it /76
also causes some new problems. They are (1) reduced thrust, (2) computation of thrust chamber parameters, and (3) life and reliability of the baffle.

1. Reduced Thrust

The flow field is changed by adding a lateral baffle in the combustion chamber. A semi-open space is created between the injector and the baffle, occupying a part of the volume in the combustion chamber. This is equivalent to a pre-combustion chamber. In this case, if we inject at the original rate, the pressure in the pre-combustion chamber will be greater than the designated pressure. If we still use this pressure for the feedback control, the needle valve opening will be reduced to cut down the flow. In other words, when a baffle is added, if we still employ the original pressure feedback scheme (the feedback pressure is measured at the bottom of the injector), the engine cannot receive the correct propellant flow under all operating conditions. Thus, the thrust is also consequently decreased.

Because of the high flow rate at the peak operating condition, the local pressure in the pre-combustion chamber rises too much. Its feedback function will greatly cut down the flow rate to reduce the thrust by a great deal.

At a low operating mode, the flow rate is small and the pre-combustion chamber volume remains unchanged. Therefore, the local pressure rise is not significant. The feedback potential essentially reflects the pressure without a baffle. Hence, the flow rate does not change much and the thrust does not drop by much. Furthermore, because the combustion efficiency is improved by the baffle, the thrust is increased. This can be confirmed by the following parameters measured under essentially identical conditions with and without the baffle, as shown in Figure 5.

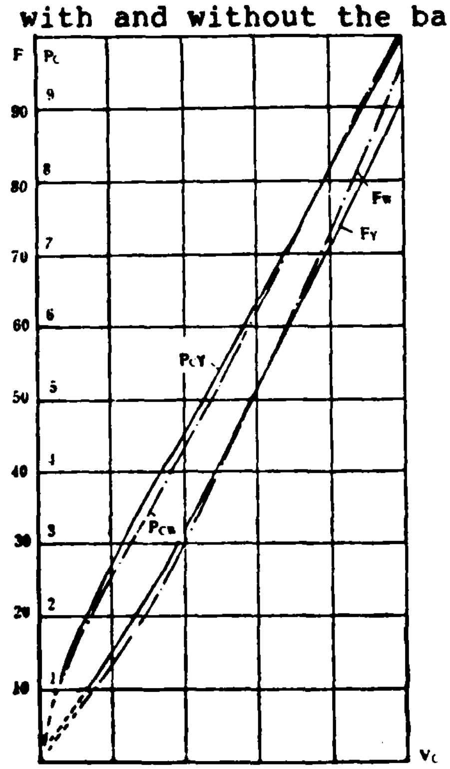

Figure 5. Comparison of Experimental Data Obtained With and Without a Baffle

2. Computation of Parameter in the Presence of a Baffle

When a baffle is present, because the pressure in the front chamber is different from that in the rear chamber, and the front chamber pressure is higher than the rear-chamber pressure, the rear-chamber pressure should be used in the computation. However, it is not possible to measure the rear-chamber pressure with the above experimental technique. It is only possible to measure the front-chamber pressure which will lead to confusion if the front-chamber pressure is used to carry out the computation. For example:

$$\begin{cases} \beta = A_t \cdot p_c / G \\ C_F = F / A_t \cdot p_c \end{cases} \quad \text{(A)}$$

Where: β - comprehensive parameter

C_F - thrust index

A_t - throat cross-sectional area

G - propellant flow rate per second

F - thrust

Based on the above equation, when β and C_F are calculated with the measured p_c, the value of β will be higher than the real value. Hence, there will be situations when the combustion efficiency is greater than 1. C_F, however, will be much smaller than the real value. This is because F is small and p_c is too large.

3. Life and Reliability of the Baffle

Baffles made of erosion materials suffer from burn-out and detachment in the high-temperature combustion gas. The burn-out problem can be solved by increasing its thickness. In this experiment, a 15 mm thickness could satisfy the designated 65 seconds of operating time.

Another aspect of the reliability of the baffle is to ensure /77 that it does not fall off during operation. It was experimentally found that the reliability of a three-legged baffle is the worst. The reliability of a multi-legged or ring-shaped baffle is higher.

VI. Solutions to Problems Caused by the Baffle

If the control system in place in the front cavity pressure feedback scheme, it is possible to employ two methods to compensate the thrust reduction due to the use of the baffle. One approach is to raise the control voltage and the other is to expand the throat radius.

These two approaches will both require comparison tests done with and without the baffle under identical operating conditions in order to determine the amount of thrust reduction ΔF caused by the baffle. Compensation is made based on this experiment.

A. Raising the Control Voltage

The basic relation is as follows:

$$\Delta F = F_W - F_Y \qquad \text{(A)}$$

Where: F_W- measured rated thrust without the baffle

F_Y- measured rated thrust with the baffle

We consider that the reduction in thrust is caused by the pressure difference in front of and behind the baffle, i.e.,

$$\Delta p_e \cdot A_m = \Delta F = F_W - F_Y \qquad \text{(B)}$$

Where: Δp_c - the pressure difference across the baffle, i.e.

$$\Delta p_c = p_o - p_c \qquad (C)$$

p_o - front-cavity pressure

p_c - rear-cavity pressure

A_{so} -solid area of the baffle (to be measured ahead of time)

Based on the above equation, once the pressure differential p_c is calculated, it is possible to calculate the increment in the control voltage corresponding to this pressure differential. The equation is as follows:

$$\Delta V_c = \Delta p_c / 1.8 \qquad (D)$$

Where: ΔV_c - increment of the control voltage.

Finally, the control voltage at the rated operating mode can be calculated according to the formula:

$$V_c = V_{cyu} + \Delta V_c \qquad (E)$$

B. Expanding the Throat Radius

It is also possible to compensate the decrease in the rated thrust by enlarging the throat radius. The basic relationship is as follows:

$$\Delta G = \Delta F / I_{spmax} \qquad (F)$$

Where: ΔG - propellant flow rate per second to be compensated

I_{spmax} - specific thrust at the rate operating condition (unchanged)

It is then possible to find the required throat area and radius:

$$\Delta A_t = \frac{dA_t}{dG}\Delta G \qquad \text{(G)}$$

i.e.

$$\Delta A_t = \frac{\beta}{p_c}\Delta G \qquad \text{(H)}$$

Therefore,

$$A_t = A_{tyu} + \Delta A_t \qquad \text{(I)}$$ /78

$$D_t = \sqrt{\frac{4}{\pi}A_t} \qquad \text{(A)}$$

A_{tyu} - originally designed throat area

ΔA_t - enlarged throat area

D_t - enlarged throat diameter

In this case, the parameters are calculated according to the following:

$$C_F = F/A_t \cdot p_c$$
$$\beta = A_t \cdot p_c/G \qquad \text{(B)}$$

Where: F - measured thrust

A_t - corrected throat area

p_c - $p_o - \Delta p_c$

p_o - front cavity pressure

G - measured per second propellant flow rate

There is a problem associated with the approach to compensate the thrust loss by raising the control voltage. The problem is that the rated thrust can be compensated to the specified value. However, the thrust is always higher than the specified value when it operates below the rated thrust. This effect is shown in Figure 6.

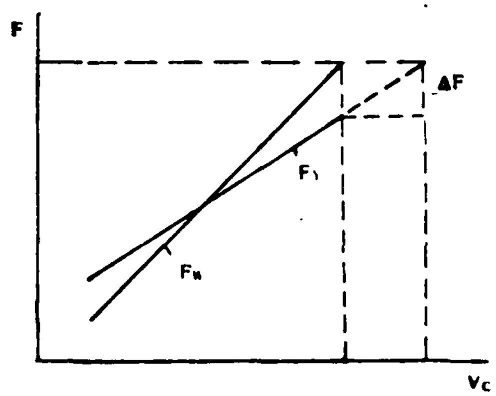

Figure 6. Thrust Curves Before and After Compensation

Using the approach to enlarge the throat diameter for thrust compensation will vary the nozzle-area ratio, which consequently will change the thrust index. If the nozzle-area ratio is to be maintained, then the nozzle will have to be re-designed. In addition, as discussed before, the thrust is reduced significantly at the high operating mode when the front-cavity pressure is used in the feedback control process. In a low operating mode, the thrust may not decrease by an appreciable amount. Or, it may not decrease at all. If the rated thrust can be achieved by expanding the throat diameter at the peak operating mode, the specified thrust may not be obtained at a lower operating mode.

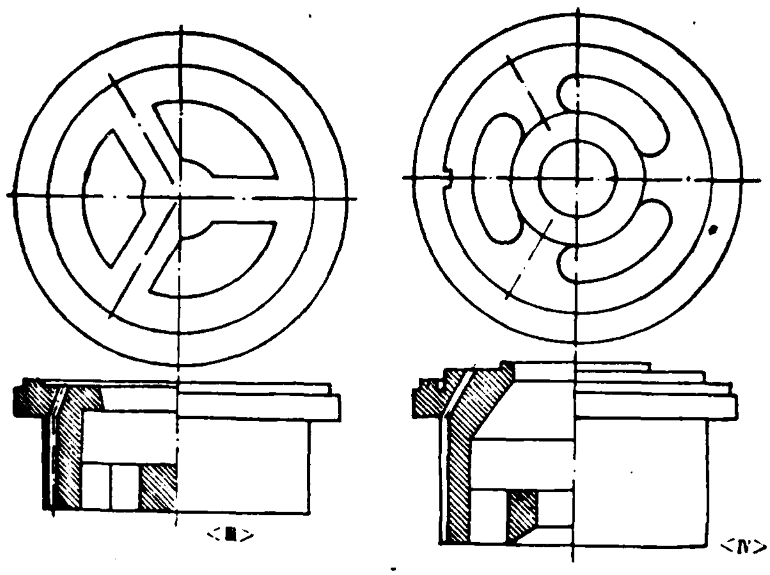

Figure 7. Baffle Plans III and IV

Based on the above analysis we understand that the thrust will not reach the original value at a specific voltage if the control method remains unchanged and the pressure measured at the bottom of the injector is still used in the feedback control of the pressure in the combustion chamber (feedback control by using the pressure in the cavity in front of the baffle) after the lateral baffle is put in place. The two compensation schemes mentioned above have their drawbacks. Besides, they are difficult to implement. Furthermore, they /79
cannot solve the fundamental problem. Therefore, the chamber pressure in the rear cavity behind the baffle ought to be used in the feedback control of the pressure in the combustion chamber. If it is achievable, all the problems can be resolved. To this end, we designed a series of complex baffles which can be used to measure the rear-cavity pressure for feedback control. The specific structures are shown in Figure 7.

VII. Preliminary Study on the Effect of the Shape and Location of the Baffle on Combustion Oscillation

It is a simple and effective measure to use a baffle to suppress combustion-chamber pressure oscillation. However, the shape and position of the baffle can directly affect its effectiveness. To this end, we conducted some experiments.

1. Effect of the Position of the Baffle

We made a comparison with three positions; i.e. 10 and 30mm behind the injector and in front of the nozzle inlet.

a. Baffle Located at 10 mm Behind the Injector

The baffle there has a stronger suppressing effect against combustion vibration. However, it is severely eroded. The life time is short. It usually burns out in approximately 80 seconds under variable operating conditions.

b. Baffle Located 30mm Away from the Injector

The baffle there has a similar strong suppressing effect on combustion vibration. Its own erosion is relatively minor and its life time is longer. It lasts approximately 100 seconds under variable operating conditions.

c. Baffle Located at the Nozzle Inlet

It has a weakened effect on the combustion oscillation. From the experimental results, we could still observe some local vibrations.

Figure 8 shows the experimental recording of the curve obtained when the baffle was installed approximately 30mm from the injector. The curve is relatively smooth.

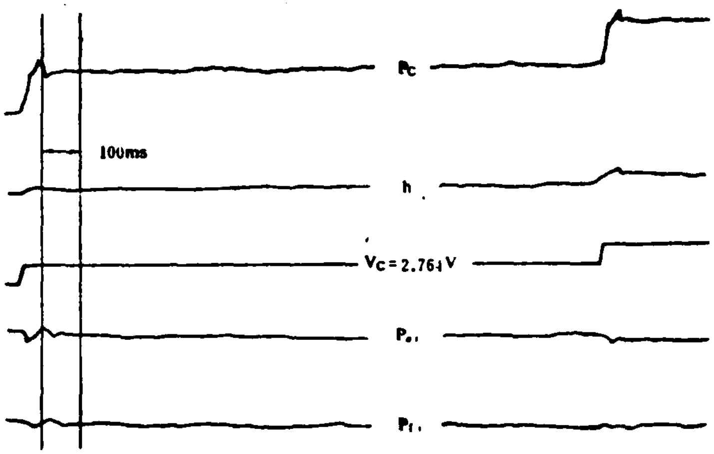

Figure 8. Curve Recorded With Baffle Installed 30mm From Injector

2. Effect of Baffle Shape on Combustion Oscillation

We selected four baffle structures (I, II, III and IV) for a comparison test. To simplify the findings, only baffle designs III and IV will be discussed here.

Plans III and IV (as shown in Figure 7) are a combination of a thermally insulated head and an anti-vibration baffle. The advantages are that (1) the head and the baffle are integrated for improved reliability, (2) the rear-cavity pressure is used for feedback control to ensure that all parameters are normal, and (3) the anti-vibration effect is better. The drawback of plan III is that it is too close to the injection plane. The jet wash and combustion gas circulation are strong. Hence, its life /80 is relatively short. Plan IV essentially overcomes this disadvantage. Therefore, it was chosen as the plan to be used in our system.

VIII. Conclusions

It is an effective and convenient measure to use a lateral baffle to suppress the combustion vibration of a variable-thrust liquid-fuel rocket engine using AK-27/UDMH as the propellant at low operating conditions. It has already been incorporated in the liquid-fuel rocket engine developed with good results.

This paper only provides some preliminary results of this problem. The theoretical analysis of the anti-vibration mechanism of the baffle, the optimal structure of the baffle and the ideal position of installation will require further studies in the future.

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