AN EXPERIMENTAL STUDY OF A RETROROCKET WITH A CYLINDRICAL BODY IN SUPERSONIC FREE STREAMS

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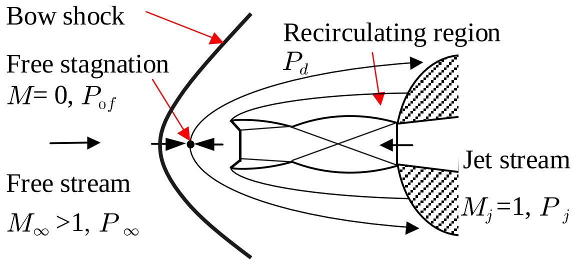
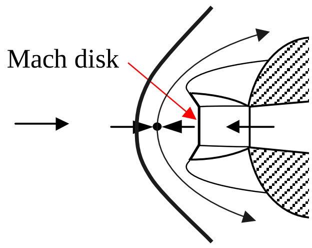
Abstract

The aerodynamic characteristics of a retrorocket in supersonic flows are studied experimentally. The wind tunnel test model has a cylindrical body with a flat face and a forward conical nozzle from which nitrogen gas is exhausted at the Mach number 3.1. The ratio of jet-exit diameter to body diameter is 0.43. Wind tunnel free stream Mach numbers are 1.5, 2.0 and 2.5. The ratio of the jet total pressure to the free stream total pressure after a normal shock is varied from 1 to 29. Measurements of axial force that the model receives together with optical observation of the flow field are made for various values of the total pressure ratio. The axial force changes abruptly at certain total pressure ratios, depending on the free stream Mach number. Schlieren pictures of those flow fields show that axial force discontinuity is due to the change of the opposing jet flow structure.



(a) Slightly under-expanded long jet : unstable



(b) Highly under-expanded short jet : stable

Fig. 1 Two types of jet structure.

1 Introduction

The retrorocket has been proposed as a device to decelerate the rocket or to protect the body from aerodynamic heating during high-speed flight. It is difficult to estimate the aerodynamic characteristics of a retrorocket because the flowfield around the opposing jet in a supersonic flow is very complicated. It has been clarified in previous studies[1, 2, 3, 4, 5] that the primary parameter that affects the flow-field is the ratio of a jet total pressure to a freestream total pressure.

Recent studies[2, 3] have investigated the flow around a sonic opposing jet, having a total pressure ratio of less than 10, for protection of a body from aerodynamic heating. Figure 1 shows a schematic flow field in which a supersonic opposing jet is emanated from the center of a hemispherical nose. When the total pressure ratio is smaller than a critical value, the flow field becomes unstable and bow shock oscillates intensely (Fig. 1(a)). When the total pressure ratio is over this value, the flow field is almost always stable and a Mach disk can be clearly observed inside the jet (Fig. 1(b)). Near the critical value, the flow field results in either these states and it tends to alter from one to another in turn. It is described that such a mechanism is caused by the

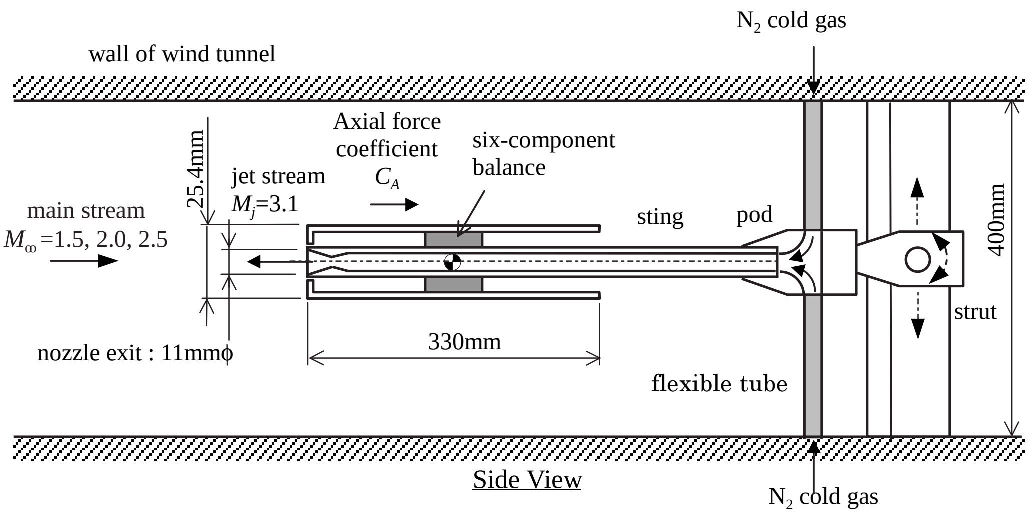


Fig. 2 Wind tunnel installation and model sketch.

pressure balance between the jet flow and the recirculating region near the jet exit.

Other practical investigations in which the jet diameter is of the same order as that of the body have done by Romeo [4] and Hayman [5]. These previous studies both cover wide range of the total pressure ratio, but it has not been clarified whether the observed phenomena may be the same as that of the sonic jet with the small nozzle-exit diameter.

This paper focuses on the aerodynamic characteristics of a retrorocket as a deceleration device with relatively large total pressure ratios and a jet Mach number higher than that of the free stream. Specifically at some free stream Mach numbers, detailed analysis have done for the flow field around a opposing jet of a retrorocket with nozzle exit Mach number of 3.1 by schlieren pictures and axial force measurements.

2 Apparatus

2.1 Wind tunnel

All measurements were made in a blowdown supersonic wind tunnel at Mitsubishi Electric Corporation, Kamakura Works with a 400 x 300 mm rectangular test section. The free stream Mach number M_∞ was set to 1.5, 2.0 and 2.5. The free stream pitot pressure P_{0f}, the total pressure after a normal shock, was 0.182 MPa in all cases. Reynolds numbers based on the model body diameter, $D_B = 25.4$mm, were about 8×10^5.

2.2 Model

Figure 2 shows the schematic of the model in the wind tunnel. The model consisted of a thin-walled cylindrical shell and a six-component balance equipped with the hollow sting with a 12° conically divergent nozzle. This nozzle had a throat diameter of 5mm and an exit diameter of 11mm, so that the jet exit-plane Mach number M_j was 3.1 if one-dimensional flow was assumed. With these apparatus, the balance could measure the axial force not including the jet reaction force. The base pressure P_B was also measured to estimate the base drag.

2.3 Gas supply for jet

Nitrogen gas from 15 MPa commercial cylinders was used for the source of jet. The total pressure of the jet P_{0j} could be controlled by a diaphragm control valve, ranging up to 5.2 MPa. This corresponded to the total pressure ratio, $P = P_{0j}/P_{0f}$, between 1 to 29.

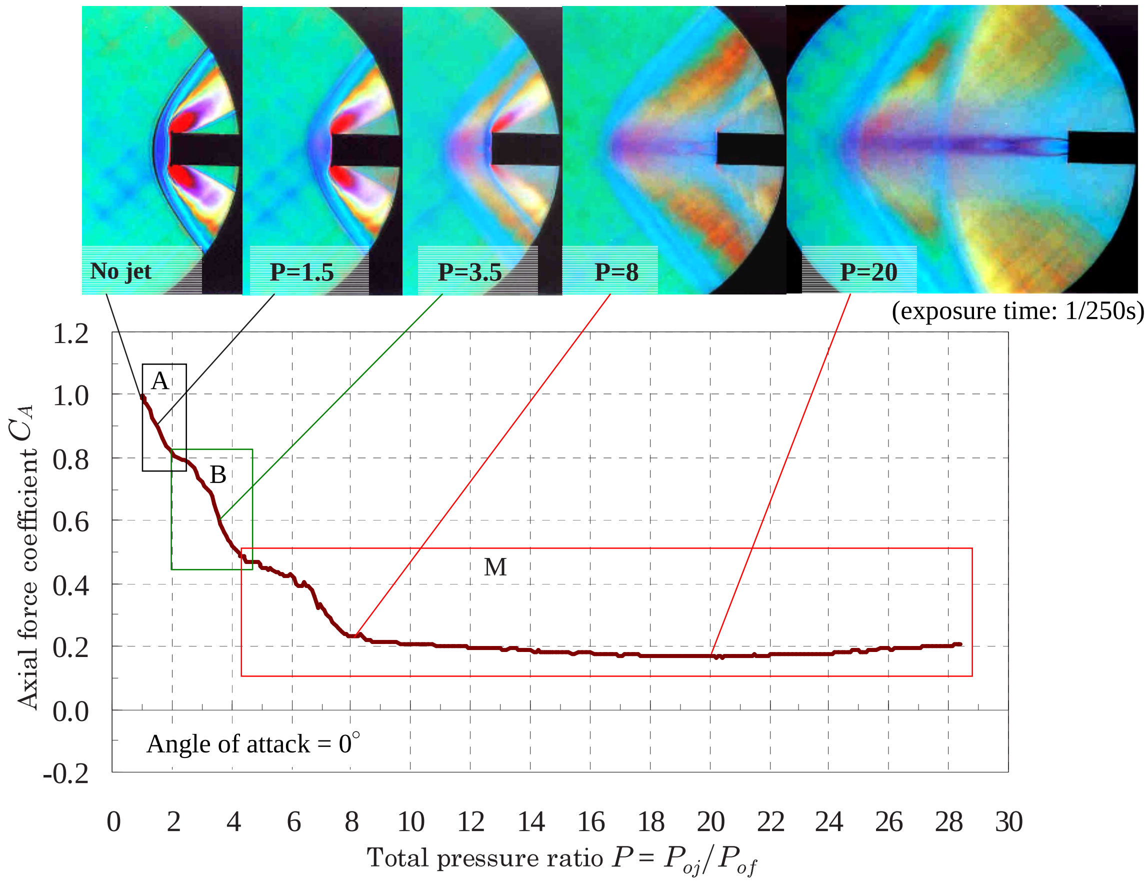


Fig. 3 Variation of Axial force coefficient C_A with total pressure ratio P and schlieren photographs of the flow. $M_\infty = 1.5$.

2.4 Test methods

The tests included balance measurements and taking schlieren pictures of the flow by a still camera and a high-speed video.

3 Results

For each free-stream Mach numbers, the test results are shown which explains how its jet total pressure affects the axial force coefficient and the features of the flow field. The axial force coefficient C_A is given by

$$C_A = \frac{F_A + (P_B - P_\infty)S_B}{Q_\infty S_R}, \qquad (1)$$

where F_A is measured axial force excluding jet thrust, P_∞, Q_∞ are the free-stream static and dynamic pressure, P_B is the pressure of the model base area, S_R is the reference area (cross-sectional area of the body) and S_B is the model base area; S_R minus the nozzle exit area.

3.1 The case of $M_\infty = 1.5$

Figure 3 shows axial force coefficient C_A that the retrorocket receives under the condition of $M_\infty = 1.5$, and some typical schlieren photographs. Generally the bigger the total pressure ratio is, the smaller the C_A becomes. The bow shock moves forward as the total pressure ratio becomes large, and at the same time the flow field structure changes a few times. The gradient of the graph changes according to the flow field structure. These flow field structure can be classified into a few categories.

As shown in figure 3, C_A is down and very steep in the region between P =1 and 2. The bow

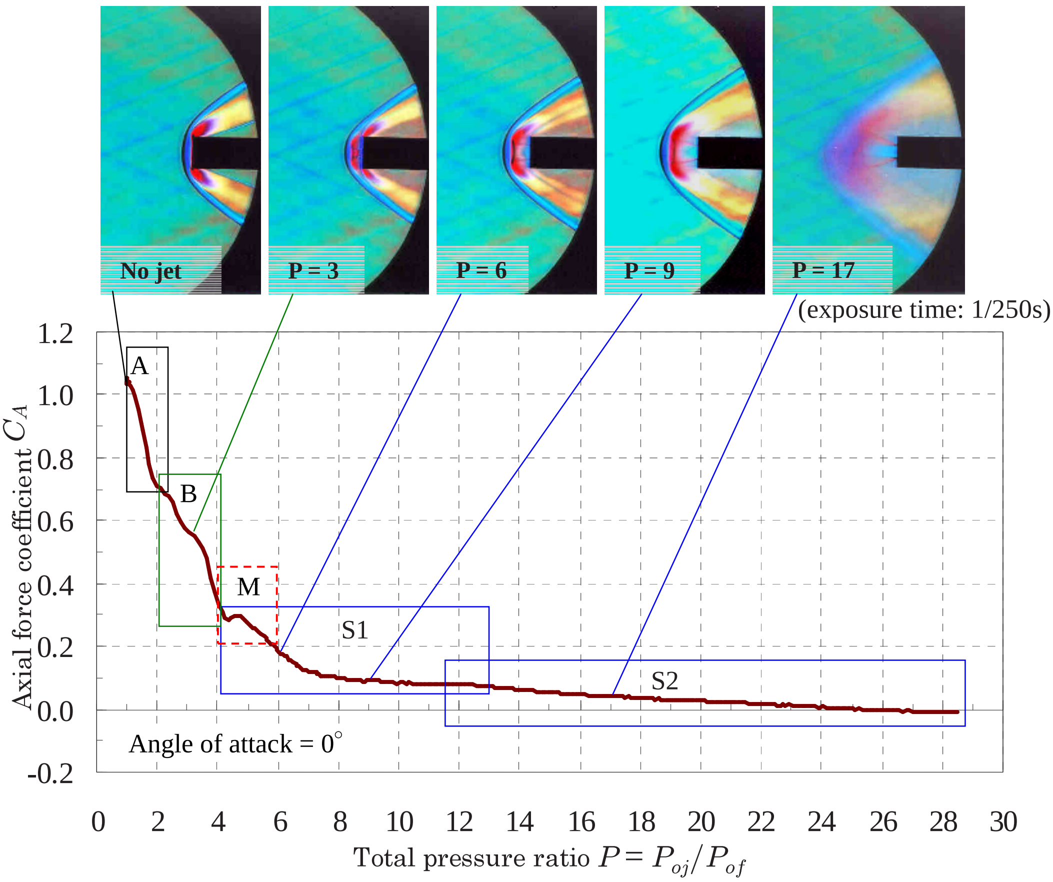


Fig. 4 Variation of Axial force coefficient C_A with total pressure ratio P and schlieren photographs of the flow. $M_\infty = 2.5$.

shock moves forward as P increases. The jet flow direction is altered quickly after the exit. This flow structure is referred to as type A hereafter.

At the point of $P = 2$, the gradient of C_A becomes a bit moderate, which only lasts little, and it becomes steep again as P increases to 4. In this region the jet flow reaches farther straight, but its bow shock moves back and forward in a very fast cycle. This flow structure is referred to as type B.

The gradient of C_A becomes moderate again when P exceeds 5. Accordingly, multi-cells structures appear in the jet stream and its length become longer as P increases to 29. This flow structure is defined as type M.

3.2 The case of $M_\infty = 2.5$

Figure 4 shows axial force coefficient C_A that the retrorocket receives under the condition of $M_\infty =$ 2.5 and some typical schlieren photographs. Likewise the case of $M_\infty = 1.5$, similar flow field structures that can be called Type A and Type B are observed in the lower total pressure ratio region. In this region C_A changes in the same way as the case of $M_\infty = 1.5$.

But when P becomes larger than 4, the flow field exhibits different characteristics from the case of $M_\infty = 1.5$. It consists of a single cell structure most of the time. Motion pictures taken by a high-speed camera have revealed that in very few cases, a multi-cell structure was formed by an instant jet stream extension when P is between 4 and 5. But most of the time, the flow field takes stable single-cell structure. Let this condition be called Type S1.

When P exceeds 12, an abrupt change in the flow field occur which results in unstable flow fields with single-cell structure maintained as it

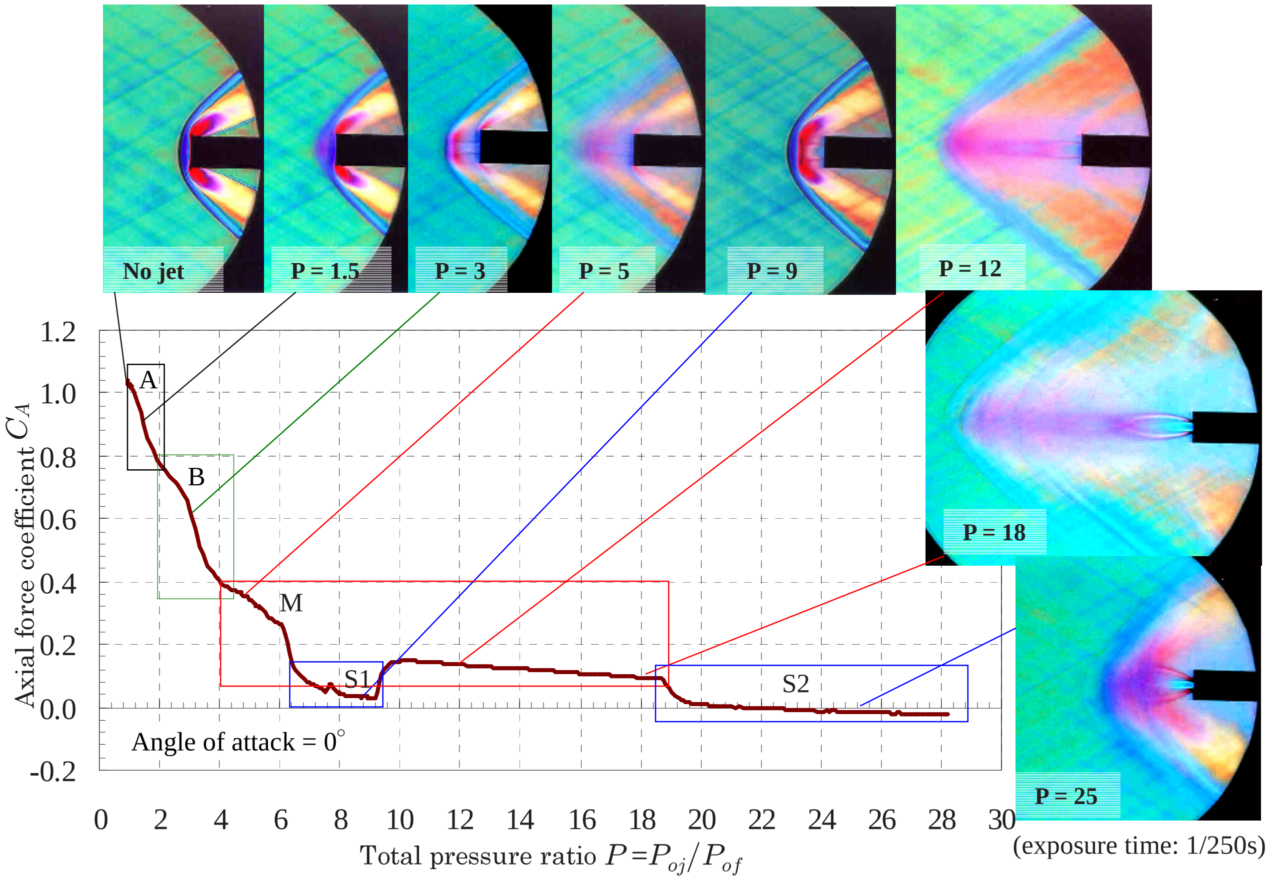


Fig. 5 Variation of Axial force coefficient C_A with total pressure ratio P and schlieren photographs of the flow. $M_\infty = 2.0$.

is. This instability is due to oscillatory displacement of the bow shock. Let this condition be called Type S2.

3.3 The case of $M_\infty = 2.0$

Figure 5 shows axial force coefficient C_A that the retrorocket receives under the condition of $M_\infty = 2.0$ and some typical schlieren photographs. Likewise other cases, similar flow field structures that can be called Type A and Type B are observed in the lower total pressure ratio region. When P exceeds about 5, a multi-cell structure similar to that of $M_\infty = 1.5$ can be observed. This can be called Type M. The total pressure ratio of between 6 and 9 make the jet stream length be short, and a very stable flow field is formed with a single-cell structure. This condition can be called Type S1. The jet stream length suddenly becomes longer to form unstable flow field with multi-cell structure when P exceeds about 9. This can be called Type M. The flow field returns to a single-cell structure when P exceeds 18. But this flow field is unstable with large oscillatory displacement of the shock wave. This corresponds to the flow field of Type S2 of $M_\infty = 2.5$ with a large total pressure ratio.

3.4 Gross axial force

The results of the gross axial force including the jet thrust are described here. Jet thrust coefficient C_T is defined by the following equation,

$$C_T = \eta \frac{S_R - S_B}{Q_\infty S_R}[(\gamma M_j{}^2 + 1)P_j - P_\infty], \qquad (2)$$

where η is the thrust efficiency, 0.9; the case of conical nozzle. Figure 6 shows C_A, C_T and gross

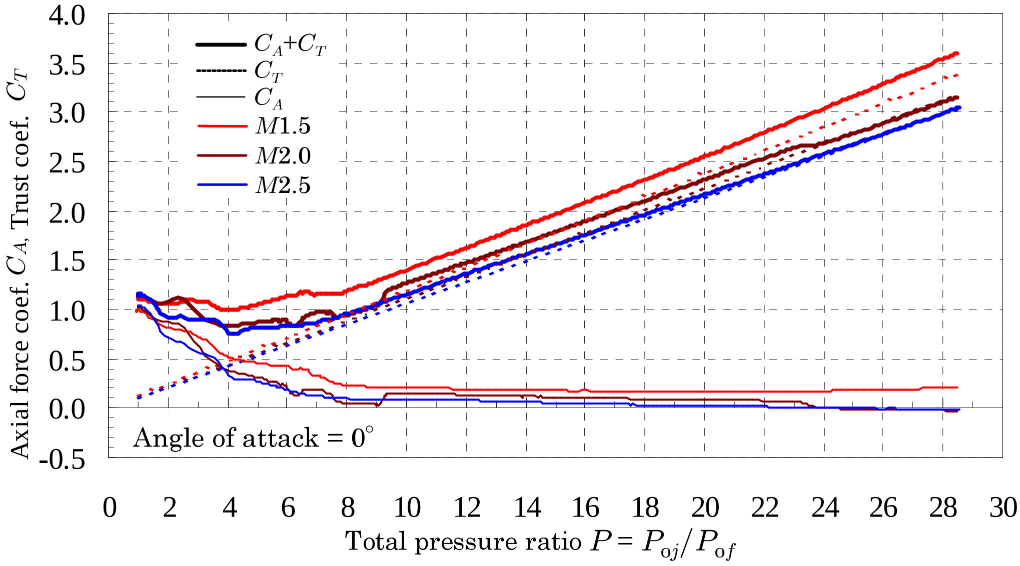


Fig. 6 Variation of thrust coefficient C_T with total pressure ratio P.

axial force coefficient, $C_A + C_T$. C_T exceeds 1 when the total pressure ratio P becomes larger than 8. Between P =1 and 8, gross axial force is less than that of no jet. The smallest value is appeared around P =4, and the value becomes smaller as free stream Mach number becomes larger.

4 Discussion

The test results have revealed that the structural change of the opposing jet can not be explained by a simple criteria like a critical total pressure ratio which has been said to separates stable and unstable regions. It is also known that several flow field structures can be realized depending on the free stream Mach number. The relation between P_j/P_d and the flow field structure can be considered as most important issue for this problem because P_j and P_d are one of the governing parameters of the flow field.

The axial force is sum of the pressure acting the flat face and the frictional force of the side wall of the model. So the average pressure of the flat face, P_d, relates C_A in the following equation,

$$P_d = \frac{Q_\infty S_R}{S_B}(C_A - C_{Af}) + P_\infty, \qquad (3)$$

where C_{Af} is the frictional force coefficient of the body. Therefore, P_d can be calculated by this equation when C_{Af} is assumed to be constant. Assuming the one-dimensional isentropic process, P_j can be calculated by the following equation,

$$P_j = P_{0j}\left(1 + \frac{\gamma - 1}{2} {M_j}^2\right)^{\frac{\gamma}{1-\gamma}}. \qquad (4)$$

Equation (3) and (4) leads to the relation depicted in Figure 7. This figure shows the relation between the total pressure ratio and P_j/P_d where C_{Af} are assumed to be 0.08 considering the reference data of the past [6]. The condition that the normal shock stays at the nozzle exit can be realized when the following equation is satisfied.

$$\frac{P_d}{P_j} = 1 + \frac{2\gamma}{\gamma + 1}({M_j}^2 - 1) \qquad (5)$$

From the equation (5), P_j/P_d at the Mach number 3.1 can be calculated as 0.09. Therefore, when P_j/P_d is smaller than 0.09, a normal shock inside the nozzle makes the nozzle exit pressure equal to P_d, which results in subsonic flow at the nozzle exit. Figure 7 shows that this condition corresponds to Type A. When P_j/P_d takes a value between 0.09 and 1, the flow in the nozzle can be described as an over-expanded jet, while under-expanded jet can be seen if P_j/P_d exceeds 1. The region, where Type B can be seen, lies between 0.09 and 0.25 of P_j/P_d, corresponding to a highly over-expanded jet.

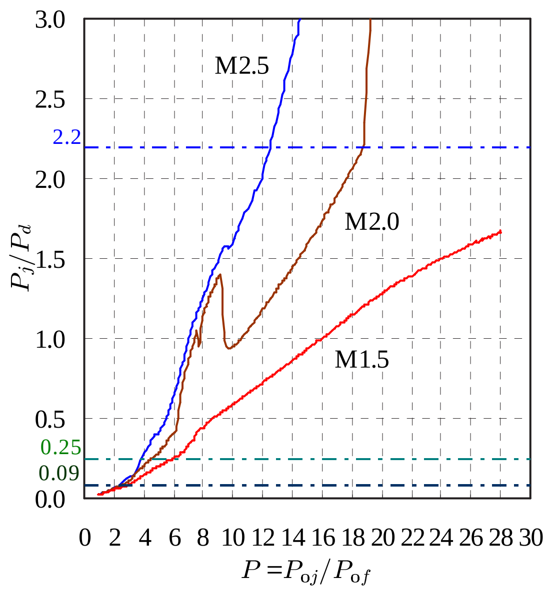


Fig. 7 Variation of nozzle exit pressure ratio P_j/P_d with total pressure ratio P.

Type S2 corresponds to the region of $P_j/P_d >$ 2.2, which is a highly under-expanded jet. In the case of Mach 1.5, P_j/P_d was well below 2.2 in all test cases. That is why Type S2 cannot be observed. When P_j/P_d takes a value between 0.25 and 2.2, the flow field structure changes depending upon a free stream Mach number. In this region, Type M (multi-cell) is the dominant structure for Mach 1.5, and Type S1 (single-cell) is the one for Mach 2.5. The jet flow structure of free stream Mach number 2.0 can take both Type M and Type S1.

In General, the opposing jet flow with a large total pressure ratio has a single cell structure because a strong normal shock is required to have large total pressure loss that is necessary to balance the jet flow total pressure and the free stagnation pressure. On the other hand, in the multi-cell structure, moderate total pressure loss takes place. This is the reason that the multi-cell structure can be realized mostly when the jet total pressure is relatively low or the free stream Mach number is small.

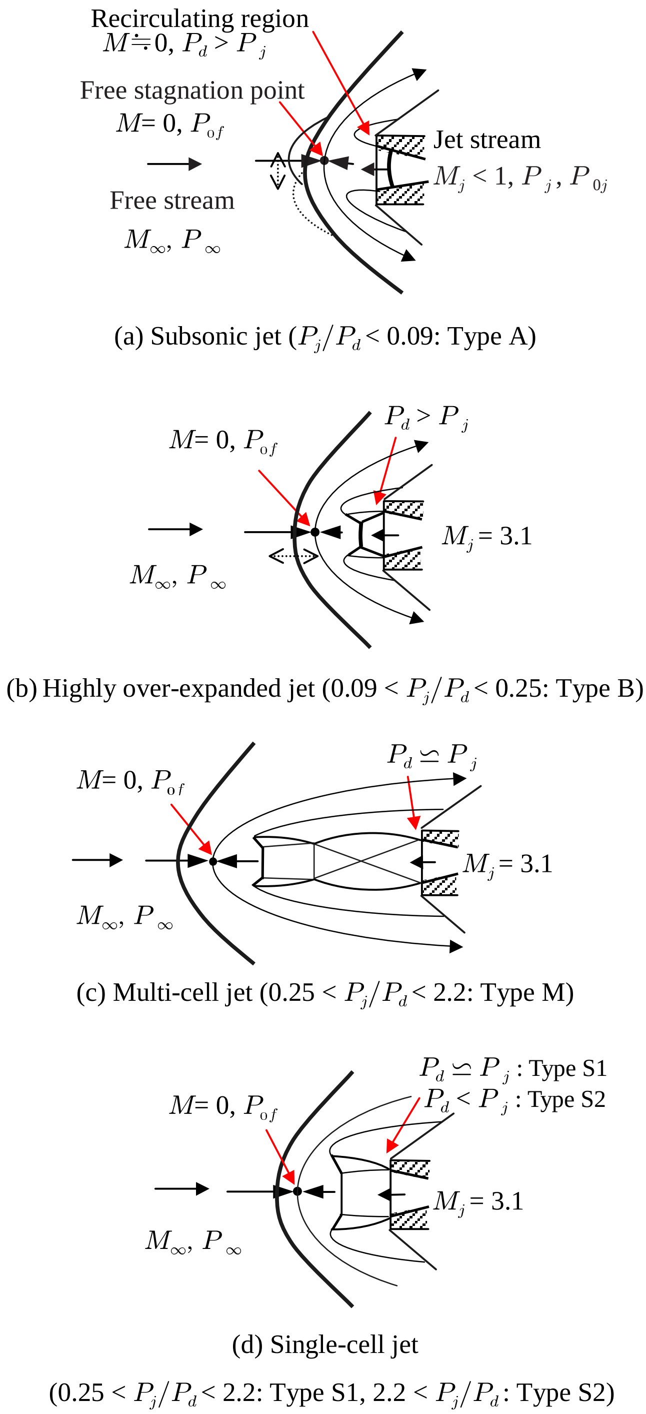


Fig. 8 Flow structure models.

With the results shown here, it can be said that the condition that needs to be satisfied to have a single-cell structure can be realized with relatively small total pressure ratio when the free stream Mach number is 2.5. On the other hand, the condition can be satisfied only by a rather big total pressure ratio with the free stream Mach number 1.5. In the case of Mach 2.0, the condition can be satisfied with P_j/P_d value of around 1, which caused the flow field structures change in turn. The relation between the jet stream structure and P_j/P_d can be summarized in figure 8. It is also mentioned that in the former research the flow structure can be classified into two categories because the opposing jet with the sonic speed at the nozzle exit cannot be over-expanded.

5 Conclusions

The results of axial force measurements and optical observations of a retrorocket with a cylindrical body in supersonic free streams have led to the following conclusions.

1. In general the axial force excluding jet thrust that the retrorocket receives becomes large as the total pressure ratio increases. However, the axial force changes abruptly with the structural change of the opposing jet.

2. Significant difference in the flow structure can be observed, which is due to the free stream Mach number. The structure of the opposing jet becomes multi-cell most of the time when the free stream Mach number is 1.5. Meanwhile the single-cell structure is the most common for the Mach number 2.5.

3. The gross axial force coefficient including jet thrust takes the minimum value when the total pressure ratio is about 4 for all free-stream Mach numbers. The bigger the free stream Mach number is, the smaller the minimum value becomes.

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