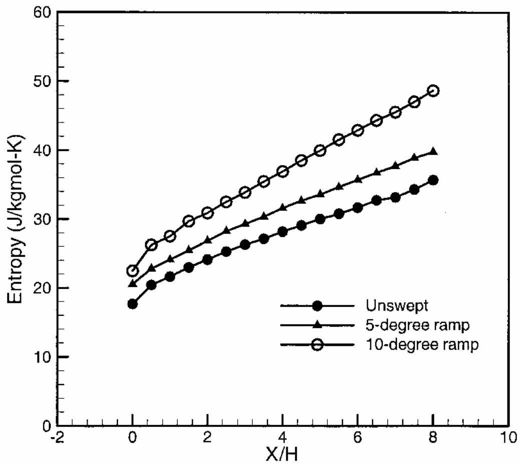

Fig. 4 Mass-averaged entropy increase.

be an intermediate case between the unswept ramp and the 10-deg swept ramp. However, the difference between the two swept ramps is not as significant as the difference between the swept ramps and the unswept ramp. This leads to the conclusion that there should be an optimum value after which further increase in sweep will not improve the mixing.

Induced mixing must be traded against losses induced by the mixing enhancement technique. The losses associated with the mixing process are shown in Fig. 4 by presenting the increase of the entropy along the flow direction. The entropy is calculated for all cells at different crossflow planes; then, the mass-averaged entropy is calculated for each plane. As expected, the 10-deg swept ramp shows higher increase in entropy than the other two ramps. Both the unswept ramp and the 5-deg ramp show the same trend. This demonstrates that the 5-deg swept ramp gives high mixing rate and low losses compared to the 10-deg case.

Conclusions

A numerical investigation has been conducted to study the supersonic mixing in a scramjet engine configuration. Three wall-mounted ramps with different side angles have been used. The study is focused on the effect of the ramp side angle in the enhancement of the mixing process. The numerical results are obtained with the existing CFD code FLUENT and with unstructured grids. Note that the swept angles highly affect the mixing process. The results show clearly that increasing the ramp side angle leads to a better mixing and faster mixing rate. The results also show that further increase of the ramp side angle will slightly improve the mixing rate. The 10-deg swept ramp is a more effective mixer than either the 5-deg or the unswept ramp. However, there is no significant difference between the two swept ramps. Furthermore, the losses associated with the 5-deg swept ramp are less than that of the 10-deg one. Further study is needed with different side sweep angles greater than 10-deg to determine if this increase will lead to further improvement of the mixing process.

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Irregular Phenomena of Shock Reflection Transition in a Conventional Supersonic Wind Tunnel

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Introduction

At a sufficiently high Mach number in steady supersonic flow, three-shock theory permits both regular and Mach reflections in the so-called dual-solution domain of incident shock wave angles. In 1979, Hornung et al.[1] predicted that a hysteresis of the transition between the two reflections would occur if the shock wave angle were adjusted during the steady flow. It was experimentally shown by Hornung and Robinson,[2] however, that the transition occurred at

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the von Neumann condition regardless of the shock angle change. Therefore, it had been believed until the early 1990s that a hysteresis effect did not exist.

Recently, two-dimensional numerical[3] and experimental[4] works demonstrated a hysteresis effect, and the existence of the hysteresis effect has been reconsidered. However, the effect observed in the experiment in Ref. 4 was a consequence of the strong three dimensionality of the wedge setup used. The three-dimensional effects of wedges were first numerically investigated in detail by Ivanov et al.[5] Sudani et al.[6] then applied the vapor-screen technique to provide an image of the three-dimensional structure of Mach reflection configuration, showing good agreement with the computations.[5] In Ref. 7, it is concluded that the three dimensionality of experimental models cannot be a cause of the transition from regular to Mach reflection in the dual-solution domain if the inlet aspect ratio of the two wedges is high enough. Actually, experiments by Sudani et al.[6] demonstrated by an asymmetric arrangement of wedges that the transition to Mach reflection occurred significantly above the von Neumann condition and that the transition back to regular reflection occurred very close to the von Neumann condition. Ivanov et al.[8] conducted several experiments in the conventional symmetric way in different types of wind tunnels and showed a clear hysteresis effect. However, questions remain why the transition happened at the von Neumann condition in Hornung and Robinson's experiment[2] and what is a dominant cause for the transition to Mach reflection in the dual-solution domain in experiments.

To study the stability of both regular and Mach reflection configurations, Ivanov et al.[9] and Khotyanovsky et al.[10] conducted numerical investigations by giving flow perturbations in the vicinity of the reflection point or in the freestream and showed that regular reflection was less stable than Mach reflection in the dual-solution domain. A physical argument of such stability considerations was provided by Hornung.[11] The experiments by Ivanov et al.[8] then indicated that the range of incident shock angle where both regular and Mach reflections were observed was wider in a freejet test section than in a closed rectangular one, and they argued that wind-tunnel disturbances had a certain effect on the results. The interest in the cause of the transition has started to center on disturbances existing in the freestream.

Sudani et al.[7] repeated the same arrangement in several series of tests, but achieved no satisfactory repeatability of the transition angle (from regular to Mach reflection). To study effects of disturbances, the freestream was deliberately seeded with water vapor. It was then demonstrated that the transition to Mach reflection happened when the water vapor arrived at the model and that no hysteresis effect was observed in the freestream seeded with water vapor. These results imply that the regular reflection is less stable in the dual-solution domain than Mach reflection and very sensitive to disturbances existing in the flow. Sudani et al.[7] also suggest experiments in a quiet (low-turbulence) wind tunnel to examine the effects of freestream disturbances directly. In this Note, the transition from regular to Mach reflection in the dual-solution domain is focused on, and experimental results obtained in a supersonic wind tunnel are presented. The repeatability of the transition angle and "irregular" transition phenomena (by which we mean transition that occurs suddenly and for no apparent reason) are discussed. Furthermore, the possibility of an irregular disturbance in the wind-tunnel flow to cause the transition is inferred. To present irregular results obtained in experiments is essential in the process of clarifying the shock reflection phenomena. Most of experiments in supersonic flow have been conducted in conventional wind tunnels, which are not specially designed for extremely low turbulence. It is also very important to understand the relation between the hysteresis phenomenon of shock reflection and wind-tunnel disturbances for the assessment of data usually obtained in each wind tunnel.

Experimental Setup

Experiments were conducted in the National Aerospace Laboratory of Japan (NAL) 1 m × 1 m Supersonic Wind Tunnel,[12] which is a blowdown-type wind tunnel with a closed test section. In this study, a test condition with a Mach number of 4 and a total pressure

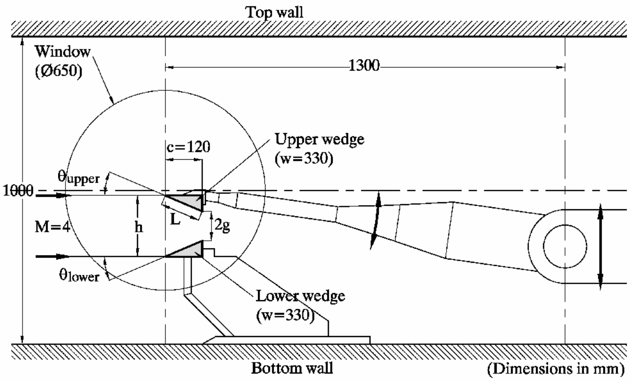

Fig. 1 Model arrangement in the test section of the NAL 1 m × 1 m Supersonic Wind Tunnel.

of 1.27 MPa was chosen. The uniform flow with constant pressure can be produced for approximately 30 s using compressed air dry enough to prevent condensation for the Mach number tested. The test section, the flexible nozzle block, and the settling chamber have recently been modified to improve the flow quality.[12] Variations in Mach number from run to run during a series of tests were within ±0.002. The noise level in the test section measured before the modification was relatively high but not serious, compared with those of other blowdown wind tunnels,[13] and is expected to become significantly lower after the modification. (This has been confirmed for lower Mach numbers than the one tested. Measurements for $M_\infty = 4$ are planned in the near future.) In this Note, mainly data obtained after the facility modification are presented.

An arrangement of two wedges is normally used in this kind of experiment to avoid viscous boundary-layer effects on a reflecting wall, as shown in Fig. 1. The width of the wedges w is 330 mm, so that the inlet aspect ratio w/h is high enough to avoid the three-dimensional effects of the wedge edges. The ratio of g to L is designed to remain approximately 0.37 (identical to that in Ref. 2). In this study, an asymmetric arrangement was applied, where the angle of attack of the upper wedge was altered during each run while the lower wedge was fixed. Even in this arrangement, criteria corresponding to the von Neumann and detachment conditions exist, as well as the conventional symmetric one (for example, in Ref. 2), as described in Ref 6. The deflection angle of the upper wedge θ_{upper} was continuously varied from a value below the von Neumann condition up to one near the detachment condition, and the transition phenomena from regular to Mach reflection were observed.

Results and Discussion

Irregular Transition Phenomena

When the upper deflection angle was increased, the transition from regular to Mach reflection occurred at a certain point in the dual-solution domain. The results in several series of tests,[6,7] however, indicated that the transition angle was not repeated satisfactorily. To check the repeatability, the upper deflection angle is increased and decreased back several times during a run, as shown in Fig. 2. In the first movement, the transition to Mach reflection occurs significantly above the von Neumann condition ($\theta_{\text{upper}} = 19.2$ deg) and below the detachment condition ($\theta_{\text{upper}} = 28.4$ deg). On the other hand, no transition is observed in the second movement. In the third movement, transition unexpectedly occurs while the upper deflection angle is fixed at 26.2 deg (significantly below the detachment condition). Nevertheless, schlieren pictures taken just before and after the transition demonstrate no observable change to cause the transition. One possible cause for the transition is thought to be disturbances of the wind-tunnel flow. The level of wind-tunnel background noise, however, should remain nearly constant during a run. (Pressure fluctuation data obtained in another series of tests have been analyzed, and the power spectra have the same trend for any periods in the run.[13]) If a high-frequency disturbance in such background noise caused the transition, the regular reflection could not

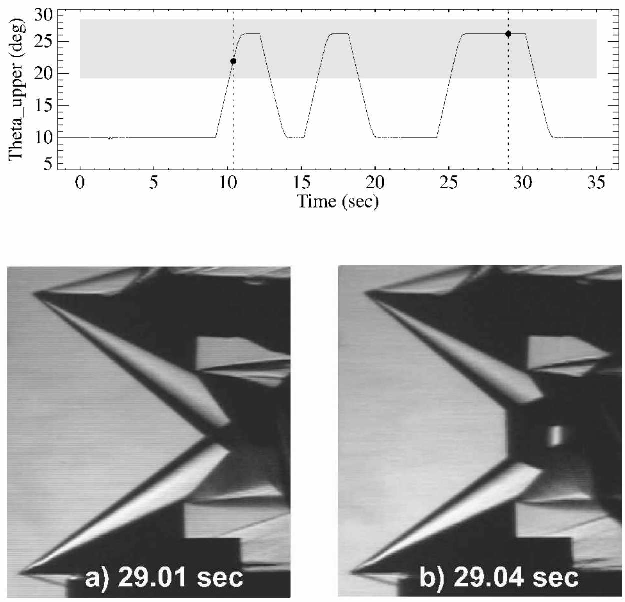

Fig. 2 Transition from regular to Mach reflection in the asymmetric arrangement of two wedges: $M_\infty = 4$ and $\theta_{\text{lower}} = 22.6$ deg: • and - - - -, points when the transition occurs from regular to Mach reflection and shaded region (upper panel), dual-solution domain.

persist for approximately 3 s after the change in θ_{upper} is stopped (26–29 s in Fig. 2). The results of Fig. 2 suggest that the transition from regular to Mach reflection can easily happen at any point in the dual-solution domain by a certain irregular factor.

To clarify what kind of disturbance dominates the transition, time histories of freestream properties acquired with a sampling frequency of 1280 Hz are examined (Fig. 3). At $t = 5$ s from the tunnel start, the settling chamber pressure P_0 and the static pressure in the test section, p, calm down, and the upper wedge starts to move at $t = 9$ s. In this run, the upper wedge makes the same movement four times. The transition occurs in every movement while the upper deflection angle is increasing. Dotted lines represents the points of the transition and are also plotted. The four transition points are located entirely on the plateaus of P_0 and p. The settling chamber temperature T_0 is gradually decreasing during the run, but the change in Reynolds number is so small that the effect is considered to be negligible. In spite of the situation in which there are no observable changes in freestream properties, the first and the second transition angles are significantly lower than the third and fourth angles. (The difference is approximately 4 deg.) Note that these transition phenomena have no relation to any disturbances with relatively low frequency that can be detected by the present pressure-monitoring system.

In Fig. 4, the transition angle obtained in two different series of tests are plotted against the time from the tunnel start. The transition phenomenon has a clear correlation with the time. Before $t = 17$ s, the transition occurs near the von Neumann condition, but after $t = 20$ s, the regular reflection can persist up to a significantly higher θ_{upper}. Although the freestream properties seem to have no change after the uniform flow is established, the regular reflection cannot be realized near the detachment condition (in a higher θ_{upper} region of the dual-solution domain) during the first half of the run.

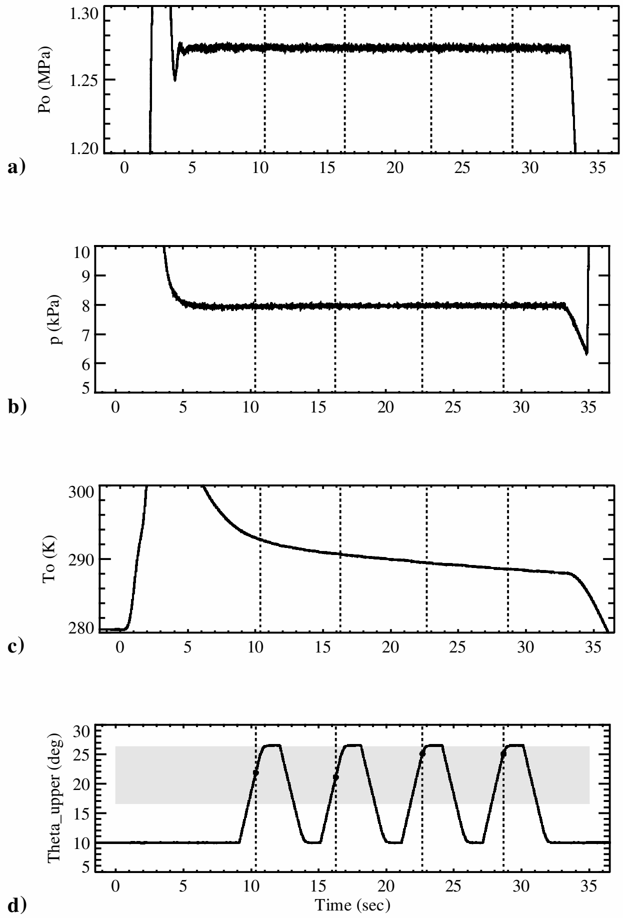

Fig. 3 Time histories of settling chamber pressure P_0, freestream static pressure p, settling chamber temperature T_0, and the deflection angle of the upper wedge, θ_{upper}, during a run: $M_\infty = 4$ and $\theta_{\text{lower}} = 25.1$ deg: • and - - - -, points when the transition occurs from regular to Mach reflection and shaded region (panel d), dual-solution domain.

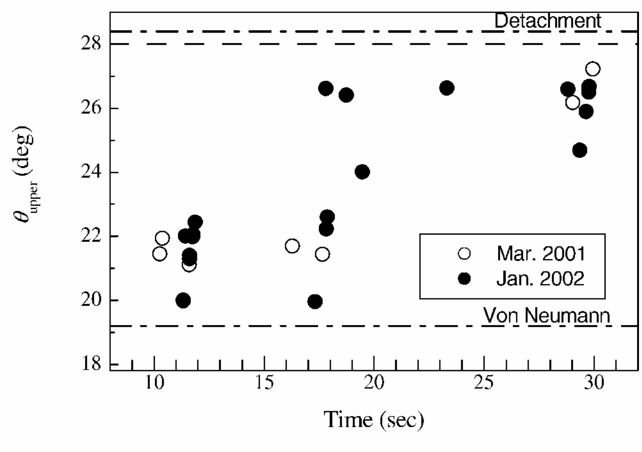

Fig. 4 Correlation between transition angle (the deflection angle of the upper wedge at the transition from regular to Mach reflection) and the time from the tunnel start: $M_\infty = 4$ and $\theta_{\text{lower}} = 22.6$ deg.

Effects of Disturbances

It is well established through experiments in various wind tunnels (for example, Ref. 8) that the transition from regular to Mach reflection in the dual-solution domain is dominated by wind-tunnel disturbances. In this Note, however, it is shown that the type of disturbance is important to the transition. Figure 4 indicates that the maximum transition angle obtained at $t = 30$ s is close to the detachment condition. The dashed line represents the condition in which the flow downstream of the reflected shock becomes subsonic, and analysis suggests that this condition is the actual point of the transition to Mach reflection. In the situation near the maximum transition angle, one can expect that the transition to Mach reflection would be possible to be induced by freestream disturbances, such as pressure fluctuations, because regular reflection becomes less stable as it approaches the detachment condition.[10] Therefore, it is thought that the maximum transition angle is determined by the uniform disturbances (such as pressure fluctuations). Thus, if the experiment were performed in a quiet (low-turbulence) wind tunnel, the transition would be able to occur very close to the detachment condition. It has actually been shown that the maximum transition angle after the facility modification is higher than before the modification. This was expected because of some improvements to the settling chamber, which are achieved as one of the major modifications of the facility.

The fact that the transition actually happens significantly below the detachment condition suggests that the irregular disturbance should exist besides the uniform ones in the freestream. Sudani et al.[7] observed the transition phenomena in the flow seeded with water vapor deliberately and demonstrated that the transition happened at the arrival of the water vapor and that no hysteresis effects were confirmed with water vapor. Effects of slight changes in freestream Mach number and static pressure by the water injection were negligibly small, as discussed in Ref. 7. Therefore, this result implies that water droplets themselves can be a cause for the collapse of regular reflection. If this were true, it would be probable that a particle, such as water droplets or dust mixed unfavorably in the freestream, had an effect on the transition. In the usual experiments, effects of small particles in the flow can be neglected because they are not critical to conventional force or pressure measurements. However, if a particle accidentally passed near the regular reflection point and collapsed the regular reflection, Mach reflection would be produced in the whole spanwise region. (Recently, we have experimentally verified that Mach reflection spreads in the spanwise direction even if it happens just at a certain regular reflection point, using a very sharp cone sticking out from downstream of the regular reflection point. More elaborate experiments are planned in the near future.) If effects of such small particles were dominant, the irregular behaviors of the shock reflection transition would be observed in other conventional wind tunnels where no special care is taken in the settling chamber or at the nozzle entrance. The present study reveals that a small irregular disturbance is more effective for the collapse of regular reflection than the uniform disturbance.

It has not been clearly understood whether a small particle can induce the transition to Mach reflection below the detachment condition. However, the transition near the von Neumann condition should be impossible by the uniform freestream disturbances because an incredibly high level of disturbance is necessary.[10] If a certain number of small particles or a certain amount of water vapor was included in the flow, it would be easily observed that Mach reflection always occurred near the von Neumann condition. In this case, experimental results would show seemingly better repeatability. On the other hand, with fewer disturbances, the possibility increases that the regular reflection can persist up to a high deflection angle (near the detachment condition). However, the irregularity becomes dominant, and this makes the repeatability worse, as observed in the present wind tunnel. Figure 4 indicates that the effects of irregular disturbance are undoubtedly decreasing during a run, but one cannot identify the disturbance at this stage because of no decisive experimental proof. (At least, water droplets are not the disturbance in the present wind tunnel because we confirm that sufficiently dry air has been supplied.) In experiments where the shock reflection or shock/shock interaction is essential, irregular phenomena should affect even force or pressure measurements. Identifying a disturbance that has such property is required to remove wind-tunnel uncertainties. Experiments to identify the disturbance are planned in the future by measuring pressure fluctuation with high frequency and by observing the transition phenomena with a high-speed video camera.

Conclusions

Experimental studies on shock wave reflection in steady flow have been made in a conventional blowdown-type supersonic wind tunnel. The transition from regular to Mach reflection occurs significantly above the von Neumann condition and below the detachment condition, but the repeatability of the transition angle is not satisfactorily achieved. It is shown that the type of disturbance in the freestream is very important to the transition phenomena. Although time histories of freestream properties indicate no decisive change during the run, the transition happens in a wide region of the dual-solution domain. However, there is a clear correlation between the transition angle and the time from the tunnel start. Freestream disturbances such as pressure fluctuations are nearly uniform during a run, so that they determine only the maximum transition angle attainable. An irregular disturbance besides the uniform ones must exist, and it dominates the transition to Mach reflection in the dual-solution domain. At this stage, the most probable cause is thought to be effects of small particles such as water droplets or dust unfavorably mixed into the flow, but the mechanism of the transition by such small particles is not yet understood. The present study suggests that the irregular phenomena may also happen in other conventional facilities and that a disturbance that dominates the transition should be identified to clarify wind-tunnel uncertainties.

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