Mach Number Effect on Supersonic Drag Reduction using Repetitive Laser Energy Depositions over a Blunt Body*

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Supersonic drag reduction performance using repetitive pulse energy depositions over blunt bodies was experimentally studied under two Mach numbers. The normalized drag reduction and energy deposition efficiency of Mach-1.92 over a 10-mm-dia. blunt-cylinder model were 8% and 1.2 at most, respectively. On the other hand, these values at Mach-3.20 over the same model were 22% and 6.2, respectively. The shock-wave deformation period using single-pulse energy deposition at Mach-3.20 was 64 μ s. This duration was shorter than that of 80 μ s at Mach-1.92, but the deformation magnitude on the model center axis of 40% at Mach-3.20 was larger than that of 15% at Mach-1.92. These experimental characteristics were consistent as solutions of the Riemann problem. Moreover, a drag reduction performance was much improved with a larger model diameter of 20 mm. Therefore, it has been experimentally demonstrated that the drag reduction performance due to energy deposition improves much at a high Mach number and with large model dimensions.

Key Words: Aerodynamics, Shock-waves, Wind Tunnel Testing, Drag Reduction, Energy Deposition

Nomenclature

A : model cross-sectional area against flow
 A_b : cross-sectional area of thermal bubble
 c_p : specific heat at constant pressure
 d : model diameter
 D : drag
 D_0 : baseline drag without energy deposition
 E : pulse energy of energy deposition
 f_e : repetition frequency of energy deposition
 L : scale length of energy deposition
 M : Mach number
 p : pressure
 P_b : input power on focal spot
 q_b : specific energy input
 St : Strouhal number
 t : time
 T : temperature
 $\mathbf{u}$: flow velocity vector
 U : upstream flow speed
 γ : specific heat ratio
 δ : shock stand-off distance
 ΔC_D : normalized drag reduction
 ΔD : drag reduction
 ΔE : pulse energy absorbed by gas
 ε : dimensionless energy of energy deposition
 η : efficiency of energy deposition
 ν : kinematic viscosity
 ρ : density
 σ : standard deviation
 ω : vorticity

Subscript

1: upstream flow
 2: behind bow shock without energy deposition
 3: in thermal bubble
 h: thermal bubble
 m: model

1. Introduction

Improving aerodynamic performance during supersonic flight by reducing wave drag is still an important issue for re-realizing commercial supersonic transport aircraft. Many shock-wave mitigation approaches such as mechanical methods or non-mechanical methods are suggested. The reduction methods for drag due to the shock-wave have been summarized in detail by Bushnell.¹⁾ The energy deposition approach²⁾ is one of the non-mechanical drag reduction approaches, the idea of which was pioneered by Georgievskii and Levin.³⁾ A large number of the experimental^{4–13)} and numerical studies^{14–21)} about drag reduction using energy deposition can be found. Some of these studies have reported that the energy deposition method is also effective to mitigate the sonic boom applying the shock-wave mitigation effect of energy deposition.^{22–24)}

The drag reduction mechanisms enabled by energy deposition have been discussed using computational fluid dynamics.^{12,15,25)} Applying energy deposition a high-temperature low-density bubble, a so-called “thermal bubble” generated upstream, and the shock-wave is weakened when interacting with the bubble; the acoustic impedance of which is lower than that of the post-shock flow. As a result, the shock-wave extrudes upstream (lens effect²⁶⁾). This interaction is followed by the generation of a vortex ring due to the baroclinic effect.^{15,27)} The pressure in the shock layer is mitigated in the vortex ring, thereby reducing the drag.²⁵⁾ This is the basic

mechanism of drag reduction using energy deposition.

Large drag reduction can be obtained either by enhancing the vorticity or increasing the residence time of the vortex in the shock layer. The vortex generated by the baroclinic term is obtained as the vector product of a density gradient and a pressure gradient in the vorticity equation:

$$\frac{d\omega}{dt} = (\omega \cdot \nabla)u - (\nabla \cdot u)\omega + \frac{1}{\rho^2} \nabla \rho \times \nabla p + \nu \nabla^2 \omega \quad (1)$$

Strong vorticity is obtained by increasing the density difference across the bubble interface and/or increasing the pressure jump across the shock-wave.

The performance of drag reduction using energy deposition is evaluated by two criteria. One is the magnitude of the drag reduction ΔD as shown in Eq. (2),

$$\Delta D = D - D_0 \quad (2)$$

where D and D_0 are drags with and without energy deposition, respectively. Normalized drag reduction can be defined by Eq. (3),

$$\Delta C_D = \frac{-\Delta D}{\frac{1}{2} \rho U^2 A} \quad (3)$$

where U is the flow speed and A is the cross-sectional area of the body.

Another evaluation is done with the efficiency of energy deposition, η .²⁾ This is expressed using the drag reduction and an input power P_b such that

$$\eta = \frac{-\Delta D \times U}{P_b} = \frac{\Delta C_D \times \frac{1}{2} \rho U^3 A}{P_b} \quad (4)$$

In the case of pulsed energy deposition, P_b can be written using the energy incident on the focal spot in the gas in each pulse ΔE and the repetition frequency f_e , as follows.

$$P_b = \Delta E f_e \quad (5)$$

Here, $\Delta E = \varepsilon p L^3$, where ε is a dimensionless energy of the energy deposition per pulse and L is the scale length of energy deposition. Hence, using these equations and $St = U/f_e L$, η can be written as follows.

$$\eta = \frac{\gamma}{2} \frac{M^2}{St} \frac{A}{L^2} \frac{\Delta C_D}{\varepsilon} \quad (6)$$

In Eq. (6), of course, the dependence of ΔC_D on control parameters is the key to obtaining a large value for η . However, the dependence is not readily obtained through a simple model. This is why experimental data is important. Additionally, M and St are important control parameters. The dependence of dimensionless pulse repetition frequency, which corresponds to St , for drag reduction has been experimented by Tret'yakov et al.²⁸⁾ From their results, the maximum drag reduction is achieved at $St \approx 1$. From the dependences of Mach number and model dimensions in Eqs. (4) and (6), energy deposition performance is expected to be improved at an even higher Mach number and larger model. Although

the Mach number effect was investigated by numerical simulation,¹⁵⁾ a direct experimental comparison has not been done. The objective of this study is to experimentally investigate the energy deposition drag reduction performance at different Mach numbers.

2. Effect of Thermal Bubble as a Solution for the Riemann Problem

In a past analysis of supersonic drag reduction using energy deposition,²⁹⁾ the importance of the heat input ratio has already been shown. Here, the Mach number dependence on the pressure field and the induced flow of this phenomena are analyzed based on compressible fluid dynamics. The interaction between a thermal bubble and a bow shock-wave is modeled as a Riemann problem.³⁰⁾ The schematic illustration of the model is shown in Fig. 1. On the center axis of the model, the states of the upstream flow behind the bow shock-wave and in the thermal bubble are labeled as state-1, -2 and -3, respectively. A thermal bubble is produced by isochorically depositing an energy of q per unit mass in state-1. Then, the heated region is assumed to isentropically expand to state-3 so that the pressure in the bubble becomes equilibrated to the surroundings in state-1. The following equations are established under the calorically perfect gas.

$$p_3 = p_1 \quad (7)$$

$$\frac{1}{\gamma - 1} RT_{1'} = \frac{1}{\gamma - 1} RT_1 + q \quad (8)$$

$$\frac{p_{1'}}{T_{1'}} = \frac{p_1}{T_1} \quad (9)$$

$$\frac{p_3}{p_{1'}} = \frac{p_1}{p_{1'}} = \left(\frac{\rho_3}{\rho_{1'}} \right)^\gamma = \left(\frac{\rho_3}{\rho_1} \right)^\gamma \quad (10)$$

$$\frac{a_3}{a_{1'}} = \left(\frac{T_3}{T_{1'}} \right)^{\frac{1}{2}} = \left(\frac{\rho_3}{\rho_1} \right)^{\frac{\gamma-1}{2}} \quad (11)$$

$$\frac{\rho_3}{\rho_1} = (1 + Q)^{-\frac{1}{\gamma}} \quad (12)$$

$$\frac{a_3}{a_1} = (1 + Q)^{\frac{1}{2\gamma}} \quad (13)$$

Fig. 1. Schematic illustration of the analysis model.

$$\frac{\rho_3 a_3}{\rho_1 a_1} = (1 + Q)^{-\frac{1}{2\gamma}} < 1 \quad (14)$$

$$Q = \frac{q}{RT_1/(\gamma - 1)} \quad (15)$$

From Eq. (14), the acoustic impedance is decreased through energy deposition. Here, for simplification, only the center axis of the model (equal to the axis on the stagnation point) is considered. The following equations are established using the normal shock relation between state-2 and state-3,

$$\frac{p_2}{p_3} = \frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma + 1}(M_1^2 - 1) \quad (16)$$

$$\frac{u_3}{a_1} = M_1 \quad (17)$$

$$\frac{u_2}{a_1} = M_1 - \frac{2}{\gamma + 1} \left(M_1 - \frac{1}{M_1} \right) \quad (18)$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)M_1^2}{(\gamma - 1)M_1^2 + 2} \quad (19)$$

$$\frac{a_2}{a_1} = \frac{(2\gamma M_1^2 - \gamma + 1)^{\frac{1}{2}} \{(\gamma - 1)M_1^2 + 2\}^{\frac{1}{2}}}{(\gamma + 1)M_1} \quad (20)$$

From the normal shock relation,

$$\frac{\rho_2 a_2}{\rho_1 a_1} > 1 \quad (21)$$

$$\frac{\rho_3 a_3}{\rho_2 a_2} = \frac{\rho_3 a_3}{\rho_1 a_1} \frac{\rho_1 a_1}{\rho_2 a_2} < 1 \quad (22)$$

From these relations, flow conditions after the interaction (u_* , p_*) can be obtained by equating the following equations.

$$\frac{u_*}{a_1} - \frac{u_3}{a_1} = -\frac{a_3}{a_1} \left(\frac{p_*}{p_1} - 1 \right) \left\{ \frac{\frac{2}{\gamma(\gamma + 1)}}{\frac{p_*}{p_1} + \frac{\gamma - 1}{\gamma + 1}} \right\}^{\frac{1}{2}} \quad (23)$$

$$\frac{u_*}{a_1} - \frac{u_2}{a_1} = \frac{2}{\gamma - 1} \frac{a_2}{a_1} \left\{ \left(\frac{p_*}{p_2} \right)^{\frac{\gamma - 1}{2\gamma}} - 1 \right\} \quad (24)$$

Therefore, p_*/p_1 is obtained applying the function of Q and M_1 .

$$\frac{p_*}{p_1} = f(Q, M_1) \quad (25)$$

$$\begin{aligned} & -(1 + Q)^{\frac{1}{2\gamma}} \left(\frac{p_*}{p_1} - 1 \right) \left\{ \frac{2/\gamma}{(\gamma + 1)\frac{p_*}{p_1} + \gamma - 1} \right\}^{\frac{1}{2}} \frac{\gamma + 1}{2} M_1 \\ & = -(M_1^2 - 1) + \frac{1}{\gamma - 1} \left[\left(\frac{p_*}{p_1} \right)^{\frac{\gamma - 1}{2\gamma}} \left\{ \frac{2\gamma M_1^2 - \gamma + 1}{\gamma + 1} \right\}^{-\frac{\gamma - 1}{2\gamma}} - 1 \right] (2\gamma M_1^2 - \gamma + 1)^{\frac{1}{2}} \{(\gamma - 1)M_1^2 + 2\}^{\frac{1}{2}} \end{aligned} \quad (26)$$

where f is obtained as the solution to the implicit equation, Eq. (26). In this way, p_*/p_2 and u_*/a_1 are also obtained as a function of Q and M_1 .

The pressure mitigation effect and induction of counter flow are major effects of energy deposition. The Mach number dependence of the post-shock pressure and that of the normalized flow velocity induced are shown in Figs. 2 and 3, respectively. The higher the Mach number, the stronger

these effects become. Particularly, at a relatively low Mach number lower than 3, the pressure mitigation effect is significant, whereas with a large value of Q , the counter-flow induction becomes significant in the higher Mach number region. These results enhance the motivation of examining drag reduction performance with energy deposition at different Mach numbers.

Fig. 2. Mach number dependence of p_*/p_2 .

Fig. 3. Mach number dependence of u_*/a_1 .

Fig. 4. Schematic view of the experimental apparatus.

One of the beam paths, 1 or 2, is used during an experiment: path 1 is for Mach-3.20, and path 2 is for Mach-1.92.

3. Experimental Apparatus

3.1. Wind tunnel

Experiments were conducted in an in-draft wind tunnel with a Mach number of 1.92 (Mach-1.92-WT) and a blow-down wind tunnel with a Mach number of 3.20 (Mach-3.20-WT). The wind tunnel system is shown in Fig. 4, and specifications of the wind tunnels are shown in Table 1. Both of the wind tunnels were connected to a common dump tank with a volume of 100 m^3 , which was evacuated down to 10 kPa or lower prior to experiments using a rotary pump with a volume flow rate of $7,500\text{ L/min}$.

Mach-1.92-WT is an in-draft wind tunnel with a square test section of $80\text{ mm} \times 80\text{ mm}$, and has been used in past studies.^{6,7,13)} This wind tunnel is started when the butterfly valve, which was installed downstream behind the test section, is opened. The Mach number, static pressure and static temperature during the experiment were 1.92, 13.8 kPa and 162 K , respectively. The test time was extended by increasing the volume of the dump tank in comparison with the time of 5 s in past studies, and the maximum available test time is 20 s . In these experiments, the test time was set to 3 s .

Mach-3.20-WT was newly installed to conduct the experiment with repetitive laser energy deposition. The supersonic wind tunnel installed in JAXA was referenced for the tunnel design. It consists of a high-pressure reservoir of up to 1.1 MPa , a pressure regulator, an electromagnetic valve, a settling chamber, a Laval nozzle, a test section, a butterfly valve and the dump tank. Four sheets of metal mesh and a honeycomb were installed in the settling chamber. The upper and lower portions of the nozzle were corrected against

Table 1. Specifications of wind tunnels.

Name	Unit	Mach-1.92-WT	Mach-3.20-WT
Mach number, M		1.92	3.20
Type		In-draft	Blow-down
Test time	s	5	3
Static pressure, p_1	kPa	13.8	12.5
Static temperature, T_1	K	163	107
Density	kg/m^3	0.29	0.41
Flow speed, U	m/s	495	661
Acoustic speed, a_1	m/s	258	207
Cross-sectional area at test section	mm^2	6400 (80×80)	1600 (40×40)

Fig. 5. Test section of Mach-3.2-WT.

boundary layer development. As shown in Fig. 5, quartz glass windows were installed in the vertical direction upstream of the test section to send repetitive pulsed laser beams. The inner surfaces of these windows were finished flush with the nozzle surface so as not to disturb the test flow. The cross-sectional area of the test section of this wind tunnel was $40\text{ mm} \times 40\text{ mm}$ and the test time, which was determined by the volume of the high-pressure reservoir, was 3 s . Prior to the experiments, the Mach number of the test

flow was calibrated using a Rayleigh Pitot tube formula and Pitot pressure measurement using a Pitot rake. At the test section, the flow Mach number was 3.2 ± 0.2 in a central rectangle with a width of 20 mm and a height of 30 mm. The static pressure and static temperature were 12.7 kPa and 107 K, respectively. While the static pressure was measured on the wall, the static temperature was evaluated using the temperature measured by a thermocouple installed in the settling chamber and assumed to be the stagnation temperature. Before the experiments, the test section was depressurized and the test flow was supplied from the reservoir when the valve at the upstream location of the test section was opened.

3.2. Measurement

The flow fields during the experiment were visualized using the Schlieren method with a high-speed camera (Shimadzu Corporation, HPV-1, 312×260 pixels, 1 Mfps maximum, 102 frames). A synchronized pulse diode laser (Cavitar Ltd., CAVILUX Smart, wavelength: 640 nm, pulse duration: 10 ns minimum) was introduced as the light source. The pulse duration of the light source was set to 10 ns in all experiments; both the time resolution and brightness of the images were much improved.

The force exerted to the model was measured by a ring-force balance system.³¹⁾ In this paper, “drag” refers to a force acting only on the frontal surface of the model.

3.3. Experimental conditions

The energy was supplied by a highly repetitive pulse laser (EdgeWave GmbH Innovative Laser Solutions, HD40I-E Nd:YVO₄ laser, wavelength: 1,064 nm, repetition frequency: up to 100 kHz, average power: up to 400 W). A 6 mm $\times$ 6 mm beam from the laser was expanded to 15 mm $\times$ 15 mm using a beam expander. The expanded beam was then reflected by three (Mach-1.92-WT) or four (Mach-3.20-WT) dielectric-coated mirrors and delivered to the wind tunnel. The thermal bubble was generated upstream of the flow by focusing the laser beam using a LightPath® GRADIUM® lens with a focal length of 60 mm. The repetition frequency of the laser pulse was set to 0–60 kHz and the pulse energy was set to 6.6 ± 0.2 mJ/pulse. An effective incident value was obtained by considering the reflection and absorption losses in the mirrors and lenses. In all experiments of this study, the laser power sent to the test section is varied only by the pulse repetition frequency: the pulse energy was set to be constant. In these experiments, Q can be evaluated in range of 10 to 100.

4. Drag Reduction Performance

The drag reduction performance of repetitive laser pulse energy deposition up to 60 kHz over a 10-mm-dia. blunt-cylinder-model under different Mach number conditions was studied experimentally using Mach-1.92-WT and Mach-3.20-WT. A temporal history of the drag for Mach-3.20-WT with a laser irradiation condition of $f_e = 50$ kHz is shown in Fig. 6. From this figure, drag was clearly decreased during laser irradiation. The baseline drag and standard deviation without energy deposition are tabulated in Table 2. The

Fig. 6. Drag history of Mach-3.20 with $f_e = 50$ kHz.

Table 2. Drag measured without energy deposition.

	D_0 [N]	σ [N]
Mach-1.92-WT	10.4	0.02
Mach-3.20-WT	13.1	0.09

Fig. 7. Normalized drag reduction against normalized input power.

baseline drag for Mach-1.92 was 10.4 N, and that for Mach-3.20 was 13.1 N. The standard deviation in the drag at Mach-3.20 was larger than that at Mach-1.92. Next, drag with energy deposition was measured; the normalized drag reduction ΔC_D was estimated using Eq. (3).

Figure 7 shows the normalized drag reduction against normalized power. The flow power input, that is the total enthalpy flux multiplied by the model projection, is incident on the model. In this figure, the efficiency of the energy deposition η was evaluated using Eq. (4) and Eq. (5). The normalized drag reduction increases almost linearly with the normalized power; the increase rate at Mach-3.20 is larger than that at Mach-1.92.

5. Discussion

5.1. Effects of Mach number

In the following, the mechanism of improving drag reduction performance at higher Mach numbers will be discussed. Sequential Schlieren images with the respective Mach numbers during the interaction between a bow shock layer and a

(a) $M = 1.92$ (b) $M = 3.20$

Fig. 8. Snapshots of the Schlieren images.

single thermal bubble are shown in Fig. 8. With each Mach number, $t = 0 \mu\text{s}$ corresponds to the instant when the thermal bubble attached the bow shock wave. In the Mach-1.92 case, the vortex ring generated by the interaction between the thermal bubble and the shock-wave can be observed in the shock layer, and the behavior of this vortex ring in the shock layer can be clearly seen. However, in the Mach-3.20 case, a vortex ring cannot be observed. The heating ratio T_h/T_1 ($= \rho_1/\rho_h$) per pulse can be estimated by these Schlieren images. Assuming the laser heating process is isochoric heating and the bubble expansion process is adiabatic expansion, the temperature of the thermal bubble is 469 K in the Mach-1.92 flow and 392 K in the Mach-3.20 flow. Using the static temperature of 163 K at Mach-1.92 and 107 K at Mach-3.20 as T_1 , T_h/T_1 per pulse is 2.9 in the Mach-1.92 flow and 3.9 in the Mach-3.20 flow.

Drag reduction performance can also be described using an average heating ratio,^{19,29)} T_h/T_1 , which is estimated for isobaric heating by

$$\frac{T_h}{T_1} = \frac{c_p T_1 + q_b}{c_p T_1} \quad (27)$$

where q_b is the specific power input obtained by Eq. (28).

$$q_b = \frac{P_b}{\rho_1 U_1 A_b} \quad (28)$$

A_b in Eq. (28) is the cross-sectional area of the thermal bubble. From the results of a reference test using a vacuum

Fig. 9. Normalized drag reduction against heating ratio.

Fig. 10. Energy deposition efficiency against heating ratio.

chamber and the same laser optics, the initial size of the heating source under an ambient pressure of 30 kPa can be estimated to be 1.0 mm. Then, T_h/T_1 can be obtained using this initial diameter. Figure 9 shows normalized drag reduction against the heating ratio. The normalized drag reduction tendency against the heating ratio was similar to the dependence on normalized input power, as shown in Fig. 7. Figure 10 shows the variation of η against the average heating ratio. The η of Mach-1.92 does not depend on the heating ratio, and was almost constant at 1.2. On the other hand, the η of Mach-3.20 increased as the heating ratio rose. The maximum value of η was achieved at 6.7. From these results, the drag reduction magnitude and efficiency of energy deposition improve as the Mach number increases. Hence, the drag reduction using repetitive pulse laser energy deposition works more effectively under the higher Mach number flow. These results are consistent with the results of Section 2.

The temporal histories of the shock stand-off distance at the centerline of the model evaluated from the Schlieren images are plotted in Fig. 11. The shock stand-off distance is normalized by a model diameter. The temporal history of the shock stand-off distance shows a similar tendency at both Mach numbers of 1.92 and 3.20. This is due to the so-called "lens effect"²⁶⁾: the shock stand-off distance increases when

Fig. 11. Time history of the shock stand-off distance on center axis.

the interaction is initiated, and then decreases to a value smaller than the initial one. As seen by comparing Fig. 8 and Fig. 11, the shock stand-off distance stayed larger than the initial value in the period that the bubble or the vortex ring stayed in the bow shock layer. After the bubble or vortex ring left the shock layer, the shock stand-off distance became shorter than the initial value before it returned to the initial value.

The difference in Mach number appears in the duration time of the bow shock extrusion and the increase in shock stand-off distance induced by the lens effect. From Fig. 11, the duration of the bow shock extrusion in the Mach-1.92 flow is $80 \mu\text{s}$ and the duration in the Mach-3.20 flow is $64 \mu\text{s}$. The duration time should roughly correspond to the flow residence time, which is characterized by d_m/U . The increase in maximum shock stand-off distance in the Mach-1.92 flow is 15%, and the maximum increment in the Mach-3.20 flow is 40%. The increase in the maximum shock stand-off distance with the higher Mach number should be related to an increase in the counter-flow velocity, which is obtained as the solution of the Riemann problem in Section 2.

The shock stand-off distance on the centerline normalized by the model diameter against the repetition frequency normalized using the flow residence time, d_m/U , is shown in Fig. 12. The circles plotted in Fig. 12 show the time-averaged shock stand-off distance, and the error bars in Fig. 12 show the maximum and minimum deflection in time variation. From Fig. 12, it can be seen that the averaged shock stand-off distances are larger as the repetition frequency increases for both Mach numbers. Under the experimental conditions, the shock stand-off distance increment in the Mach-1.92 flow is about 30% and that in the Mach-3.20 flow is about 60%. The increment ratio of Mach-3.20 is approximately two times larger than that of Mach-1.92. The time variation of Mach-3.20 is larger than that of Mach-1.92. This corresponds to the shock-wave deformation characteristics induced by a single pulse, as shown in Fig. 8.

5.2. Effects of thermal bubble normalized diameter

Because the normalized diameter of the thermal bubble d_h/d_m is an important parameter for drag reduction using energy deposition,²⁹⁾ drag reduction performance using two

Fig. 12. Shock stand-off distance against repetition frequency.

Fig. 13. Time history of the shock stand-off distance on center axis.

Fig. 14. Shock stand-off distance against repetition frequency.

model diameters of 10 and 20 mm under the same energy deposition condition were examined in the Mach-1.92 flow. The d_h/d_m was 0.36 and 0.18, respectively, because the incident bubble diameter d_h estimated using Schlieren images is 3.6 mm in the Mach-1.92 flow. The temporal history of the shock stand-off distance with single-pulse energy deposition and the time-averaged shock stand-off distance against the repetition frequency are shown in Fig. 13 and Fig. 14, re-

Fig. 15. Normalized drag reduction against heating ratio.

spectively. In Fig. 13, the history of the normalized shock stand-off distance variation strongly depends on the model diameter. In the case of $d_m = 20$ mm ($d_h/d_m = 0.18$), the peak value of the normalized shock stand-off distance is smaller but the duration of the extrusion is longer. On the other hand, from Fig. 14, the normalized shock stand-off distance based on the model diameter and flow speed does not depend on the model diameter. These results can be interpreted as follows. If the Mach number is the same, the normalized shock stand-off distance δ/d_m is constant because the flow field is similar. The remaining time of the vortex ring in the shock layer τ is determined by U/δ , where U is the flow speed. Therefore, τ is proportional to d_m . From Figs. 8 and 13, the shock-wave is deformed in the period that the vortex ring stays in the bow shock layer. Hence, the duration of shock-wave extrusion is longer with the larger model diameter. On the other hand, the shock-wave deformation magnitude does not depend on the model diameter because the magnitude is determined mainly by the condition in the thermal bubble and the strength of the shock-wave.

The drag reduction performance and efficiency of energy deposition against the heating ratio are shown in Fig. 15 and Fig. 16, respectively. Both the drag reduction and efficiency of energy deposition are improved with smaller value for d_h/d_m or when the model diameter is increased; in particular, η is drastically improved. This dependence of drag reduction on the normalized diameter of the thermal bubble is consistent with a previous study.³²⁾ These results indicate that the model dimension affects the vortex ring remaining time, and drag reduction performance strongly depends on the bubble residence time in the shock layer. Hence, further improvement in drag reduction performance using repetitive energy deposition can be achieved using a larger model. Or, for a given model dimension, a small amount of energy can be efficiently input for drag reduction. This implies that over the whole part of a flying body, this energy deposition scheme is expected to be efficiently done not by depositing a large amount of power to a specific location but by widely distributing a small amount of deposited powers to many locations.

Fig. 16. Energy deposition efficiency against heating ratio.

In the present study, because of facility size limitations the model diameter effect could not be investigated in the Mach-3.20-WT, in which a much more efficient drag reduction performance is expected.

6. Conclusion

Drag reduction performance using repetitive laser energy deposition over the same blunt body at two Mach numbers was experimentally investigated. The drag reduction and efficiency of energy deposition at each Mach number were increased as repetition frequency increased. The normalized drag reduction ΔC_D increased from 6% in the Mach-1.92 flow to 40% in the Mach-3.20 flow with the same heating ratio; the maximum efficiency of energy deposition was improved from 1.2 to 6.7. Therefore, better drag reduction performance using repetitive energy deposition was obtained with the higher Mach number. From the visualization results of single-pulse energy deposition, the shock-wave extrusion due to the lens effect was increased from 15% at Mach-1.92 to 40% at Mach-3.20, although the duration of the shock-wave extrusion was shortened from 80 μ s at Mach-1.92 to 64 μ s at Mach-3.20.

In addition, under the same Mach number and energy deposition scheme, the drag reduction and efficiency of energy deposition improved as the normalized diameter of the thermal bubble decreased; the normalized drag reduction increased from 6% with the 10-mm-dia. model ($d_h/d_m = 0.36$) to 45% with the 20-mm-dia. model ($d_h/d_m = 0.18$), and the maximum efficiency of energy deposition improved from 1.2 with the 10-mm-dia. model to 8.2 with the 20-mm-dia. model. These improvements in normalized diameter were consistent with extending the vortex ring residence time in the shock layer.

From these results, it has been experimentally demonstrated that drag reduction performance using repetitive laser energy deposition is improved at higher Mach numbers. Additionally, it has been confirmed that decreasing the normalized diameter also improves drag reduction performance under same Mach number and same energy deposition scheme.

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