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Study of Interaction between Unsteady Supersonic Jet and Vortex Rings Discharged from Elliptical Cell

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Abstract. The unsteady supersonic jet formed by a shock tube with a small high-pressure chamber was used as a simple alternative model for pulsed laser ablation. Understanding the vortex ring formed by the shock wave is crucial in clarifying behavior of unsteady supersonic jet discharged from elliptical cell. The purpose of this study has been to reveal behavior of the supersonic jet and the vortex rings. The unsteady behavior of a flow is investigated numerically by solving the axisymmetric two-dimensional compressible Navier-Stokes equations. The system of the calculation is a model of laser ablation of a certain duration followed by discharge through the cell exit. The parameters for the calculations are the pressure ratio of the shock tube and the cell diameter. As a result, it was found that the diameter of the elliptical cell had the effect on the interaction between vortex rings and the jet.

1. Introduction

Pulsed laser ablation (PLA) is a promising technique that has been applied to grow high-quality thin films. This technique has recently been used for the preparation of nano-clusters in gas phase [1]. Subsequently, thin films can be formed by layering the clusters discharged through pulsed lasing, and the optimal size cluster can then be selected through conventional pulsed laser deposition [2][3].

Iwata et al. [4] proposed a method for producing monodispersed clusters, which is expected to allow the direct generation of monodispersed clusters. This method uses an interaction phenomenon between the plume and shock wave arising in an elliptical cell following a laser ablation in inert gas. For simplifying the numerical analysis, the laser-ablated plume is substituted with a supersonic jet formed by a shock tube with a small high-pressure chamber can describe the pulsed expansion dynamics of the gas flow. This approach is a good alternative to describe gas ejection from the target during PLA. The high-pressure gas region formed by the laser irradiation, the laser-ablated plume, and the substrate correspond to the shock wave with a small high-pressure section, the supersonic jet injected from the shock tube, and the impingement plate, respectively.

Sakamoto et al. proposed vortex ring formation due to shock wave discharge from the exit of the elliptical cell [5]. Kitazono et al. performed a parametric study to demonstrate the effect of pressure

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1 ratio on the interaction among vortex rings and the supersonic jet [6]. However, it is not clear the effect of diameter of the elliptical cell on the interaction among vortex rings and the supersonic jet. Therefore, we investigated the behavior of vortex ring and jet in the present study.

2. Numerical Method and Boundary Conditions

The axisymmetric two-dimensional compressible Navier-Stokes equations, which can be derived from the continuity, momentum and energy equation, are solved using the finite-volume method with the total variation diminishing scheme in curvilinear generalized coordinates [7]. The inviscid flux is evaluated by third-order Roe's approximate Riemann solver [8]. The grid number is 1259 x 713. In later work by Kitazono et al., the present calculation has already proven to accord with the experimental result [6].

Figure 1 shows the elliptical contours. Three contours indicate the maximum and minimum diameters of the elliptical cell, and shape in the middle shows the standard elliptical cell. The flat plate is installed downstream of the elliptical cell. The symbols represent the focal points for $D_m/D = 3.04$ -6.00, where D_m is the cell diameter at x/D = 4.00 and D is the diameter of shock tube, respectively, and x is the horizontal distance from the exit of the shock tube. The flow field is shown in Figure 2. For the boundary conditions, non-slip conditions are applied to the cell wall. The parameters for the calculations are the cell diameter D_m/D and the pressure ratio P_h/P_b , where P_h and P_b are the pressure of the high-pressure area and backpressure. The downstream area of the elliptical cell is focused on to investigate the jet and the vortex rings generated by the shock wave.



Figure 1. Calculation shape and focal point.



Figure 2. Flow field for computation and boundary conditions.

3. Results and Discussion

3.1. Interaction between jet and vortex ring

Figures 3(a)-(h) show the calculated vorticity contours and computer schlieren images for $P_h/P_b = 22.6$ and $D_m/D = 4.47$, where *t* denotes the time elapsed from the moment of the jet injection. Figure 3(a) shows the first vortex ring. Figure 3(b) shows the second generated vortex ring immediately downstream of the cell exit. We refer to first generated vortex ring and second generated vortex ring as "VR₁" and "VR₂", respectively. VR₂ is formed by VR₁ because of Kelvin-Helmholtz instability [6]. Figure 3(c) shows the jet discharged from the cell exit. In Figure 3(d), the distance among VR₁, VR₂, and the jet decreased as compared with that in Figure 3(c). Figure 3(e) shows the interaction among VR₁, VR₂ and the jet, and Figure 3(g) depicts VR₁ and VR₂ merging into the merging vortex ring (VR₁₂). At this time, the jet is closer to the flat plate than VR₁₂, which shows that the jet passes through the vortex ring because the velocity of the jets is higher than those of the vortex rings. Figure 3(h) shows the jet impingement with the flat plate.

For the interaction between the jet and the vortex ring, it is important to determine the effect of the vortex rings on the jet velocity. The time history of wall pressure on the center of the flat plate and the jet velocity for $P_h/P_b = 22.6$ and $D_m/D = 4.47$ are shown in Figure 4. In figure 4, the times of the indicated by (c)-(h) correspond to those of figures 3(c)-(h). As shown in figure 4, the jet velocity increase during the period of $t = 624 \ \mu s$ and $t = 688 \ \mu s$. The jet acceleration during the period of $624 \ \mu s$ and $688 \ \mu s$ in figure 4 is attributed to the interaction with the vortex ring in figure. 3(d)-(f).

For the quality of thin film, it is important to discuss the static pressure at the substrate [9]. As shown in figure 4, there is a peak at $t = 864 \mu s$. This peak is caused by the jet impingement on the flat plate.



Figure 3. Vorticity and computer schlieren variation for $P_h/P_b = 22.6$ and $D_m/D = 4.47$. (VR₁: First generated vortex ring; VR₂: Second generated vortex ring; J: Jet head.)



Figure 4. Time history of wall pressure on the center of the flat plate and jet velocity for $P_{h}/P_{b} = 22.6$ and $D_{m}/D = 4.47$.

3.2. Effect of diameter of elliptical cell

Figures 5(a)-(h) show the calculated vorticity contours and computer schlieren images for two different diameters of the elliptical cell $D_m/D = 3.04$ and 6.00, where the rest of conditions are the same as for Figures 2. In Figure 5(a) shows VR₁, VR₂ and the jet are observed. This tendency is the same as that in the case of $D_m/D = 4.47$. Figure 5(b) shows the interaction between VR₁ and VR₂. Figure 5(c) shows the impingement of VR₁ and VR₂ on the flat plate. Figure 5(d) shows the jet impingement on the flat plate. It is found that the interaction between the jet and the vortex ring does not occur for $D_m/D = 3.04$ differently to $D_m/D = 4.47$. The reason for no interaction is that the cell diameter is smaller than that of the standard elliptical cell. The smaller diameter makes the shock wave reach in the arrival time at the cell exit earlier than that for the standard elliptical [10]. Therefore, the vortex rings for $D_m/D = 3.04$ are generated earlier than those for the standard elliptical cell.

Figure 5(e) shows the jet discharged from the cell exit, where VR₂ stagnate. Figure 5(f) shows the interaction between the jet and VR₁. Figure 5(g) shows VR₁, VR₂ and the jet merging. Figure 5(h) shows and the jet impingement on the flat plate. It is found that VR₁, VR₂ and the jet for $D_m/D = 6.00$ merge at the same time downstream of the cell exit differently to $D_m/D = 4.47$.

Figure 6 shows the time history of the jet velocity for $D_m/D = 3.04$, 4.47 and 6.00, the pressure ratio $P_h/P_b = 22.6$, respectively. In figure 6, the times of the indicated by (c)-(h) correspond to those of figures 5(a)-(h). As shown in figure 6, the jet velocity for $D_m/D = 3.04$ decreases during the period of $t = 648 \ \mu s$ and $t = 837 \ \mu s$ due to the decline of the jet momentum. On the other hand, the jet velocity increases for $D_m/D = 4.47$ and 6.00 during the period of $t = 624-688 \ \mu s$ and 726-763 μs , respectively, due to the interaction between the jet and the vortex ring.

The jet velocity at x/D = 11.0 for $D_m/D = 3.04$, 4.47 and 6.00 is plotted against P_h/P_b in figure 7. As shown in figure 7, the jet velocity first increases for $D_m/D = 3.04$, 4.47 and 6.00 at $P_h/P_b = 10.7-22.6$, 10.7-20.0 and 22.6-47.4, respectively, due to the fact that the initial jet momentum is proportional to P_h/P_b . Furthermore, the jet velocity decreases for $D_m/D = 3.04$ and 4.47 at $P_h/P_b = 22.6-29.0$ and 20.0-47.4, respectively. This is suggestive of the effect of the vortex ring at the cell exit. However, the detail reason is not clear at this moment. Moreover, the jet velocity remains practically constant for $D_m/D = 3.04$ at $P_h/P_b = 29.0-47.4$.



(e) $t = 573 \ \mu s$ (f) $t = 645 \ \mu s$ (g) $t = 705 \ \mu s$ (h) $t = 921 \ \mu s$ **Figure 5**. Vorticity and computer schlieren variation for $P_h/P_b = 22.6$. ((a)-(d) : $D_m/D = 3.04$, (e)-(h): $D_m/D = 6.00 \ VR_1$: First generated vortex ring; VR₂: Second generated vortex ring; J: Jet head.)



Figure 6. Time history of jet velocity for $D_m/D = 3.04$, 4.47 and 6.00.



Figure 7. Jet velocity versus P_h/P_b for $D_m/D = 3.04$, 4.47 and 6.00.

Conclusion

The purpose of the present study is to investigate the influence of the cell diameter and the pressure ratio on the jet and the vortex ring downstream of the elliptical cell. The parameter of the calculations are the cell diameter and the pressure ratio. The conclusions can be summarized as follows:

- 1) The jet velocity for $P_h/P_b = 22.6$ and $D_m/D = 4.47$ greatly increases during the period of $t = 624 \ \mu s$ and $t = 688 \ \mu s$. This is due to the interaction between the jet and the vortex ring.
- 2) The peak wall pressure on the center of the flat plate occurs at $t = 864 \ \mu s$ for $P_h/P_b = 22.6$ and $D_m/D = 4.47$. This is due to the jet impingement on the flat plate.
- 3) The interaction between the jet and the vortex ring does not occur for $D_m/D = 3.04$. At the same time, the jet velocity decreases during the period of t = 648 and t = 837 µs as a result of the decline of the jet momentum.
- 4) The interaction between the jet and the vortex ring occurs for $D_m/D = 4.47$ and 6.00. Accordingly, the jet velocity increases as a result of the interaction between the jet and the vortex ring.
- 5) The jet velocity first increases for $D_m/D = 3.04$, 4.47 and 6.00 at $P_h/P_b = 10.7-22.6$, 10.7-20.0 and 22.6-47.4, respectively, due to the fact that the jet momentum is proportional to P_h/P_b .

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