EXPERIMENTAL AND NUMERICAL STUDY OF SHOCK WAVE TRANSFORMATION BY LASER-INDUCED ENERGY DEPOSITION

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Introduction

Development of modern plasma technologies has stimulated high interest to their application for a remote high speed flow control by energy deposition (ED) using optical, microwave and electric discharges (Fig. 1), see, e.g. surveys [1–6]. As was concluded, such ED can be applied to achieve some positive global aerodynamic effects (e.g., drag reduction, lift and moments control) as well as for a localized flowfield control to minimize various negative effects (e.g., local pressure and heat transfer peaks, surface pressure fluctuations, crossing shock wave structure transformation and others). We mention a few existing examples. Promising results of early numerical predictions of drag reduction by steady and pulsed repetitive ED located upstream of blunt bodies (see, e.g. [7, 8]) have stimulated wide experimental studies. For example, effect of laser-induced ED on the bow shock of blunt body was examined in experiments [9] using single and pulse repetitive optical discharge (OD) in the air flow. As was shown, the realized flowfield structure during a stage of the lens-type transformation of bow shock in single thermal spot is close to predicted one in the numerical calculations on a basis of Euler equations. Optical flow visualization of pulsed repetitive OD in argon was performed in [10] and the capability of drag reduction of sphere-cylinder and cone- cylinder test models by the high-frequency OD was demonstrated in [11]. Additional analysis of experimental data and calculations at wide range of the Mach number was presented in [12].

The use of pulsed repetitive OD for supersonic flows control is of high practical interest. Some numerical calculations have been performed to understand unsteady flowfield properties in such conditions (see, e.g. [13–15]). Nevertheless, CFD reliability must be supported by a comparison with a wide experiment. Such attempts have been done by the authors in [16–18], where a comparison was performed with various existing experimental data (development of single OD in quiescent air [19], single OD interaction with a sphere at \(M_\infty = 3.45\) [20], pulsed periodic OD in argon [11] upstream spherically blunt and sharp axisymmetric bodies). Current joint experimental/numerical investigation is aimed to further analysis of flowfield structure development of single and double-pulsed OD and their interaction with blunt body. In particular influence of the distance between discharge and body, deposed energy level and delay between subsequent pulses were investigated.

Test models, wind tunnel and measurement techniques

The investigations were conducted in the Ludwieg Tube Facility at DLR Göttingen [21]. It has the test section diameter of 0.5 m and a run time of about 0.35 s. The free-stream conditions remain constant during the whole test campaign: Mach number of 2 at a Reynolds number, based on the body’s diameter, of \(1.54 \times 10^6\), the stagnation pressure \(1.8 \times 10^5\) Pa, stagnation temperature 270° K.

The wind tunnel tests have been carried out using a simplified axially symmetric hemisphere-cylinder model with a diameter of 60 mm and a length of 200 mm at zero angle of attack. The optical discharge upstream of the hemisphere was induced by a focused laser beam penetrating the test model along the longitudinal axis. The optical path of the laser beam is shown schematically in the Fig. 2. Before this beam penetrates the test section window it is reflected by an external mirror to-

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towards the optical channel entry on the side wall of the model, then they reaches the internal mirror and turns round along the longitudinal channel in the upstream direction to the converging lens device. The smallest channel’s diameter was 10 mm, so that the laser beam with approximately 9 mm diameter was well-suited. The exchangeable convex lens is mounted axially symmetric in the front of the model as flash as possible to the nose surface. The distance from the lens middle plane to virtual nose position of the hemisphere was round 4 mm. The distance between the laser beam focal point and nose of the model was varied in the tests from 46 mm up to 146 mm. The most measurements were made by a distance of 76 mm (corresponding to a lens with a focal length of 80 mm).

As source of energy a CONTINUUM Surelite™ PIV III laser was used in the tests. That is a flashlamp pumped Nd:YAG laser for dual pulse applications. Two laser heads are mounted on a single compact platform, providing symmetrical output beam at 532 nm that consists of two pulses with equivalent beam uniformity and polarization and pulse duration of approximately 5 ns at 10 Hz. For the present investigations the special features of this laser system were used, which make it possible to change the output power of each laser head independently from the other up to 420 mJ/Pulse and to reduce the time delay between both pulses by external triggering with nanosecond precision from any desired down to 0 ns.

The laser beam energy transferred to the discharge region was varied as parameter in the present investigations. Careful calibration tests of whole set-up were made before and after the wind tunnel test campaign with a precision power meter. The power measurements of both laser heads used were made at different positions along the optical path. So the optical power was measured not only directly at the output shutter of the laser, but also at the position of the internal mirror of the model, to quantify the losses of energy on the way (possible losses due to reflection, transmission and emission). Furthermore, the power measurements after the optical discharge give needed information about the residual energy at different power levels, which could not be emitted by the air or radiated by the light. The absorbed energy, which was spent in each of runs only for flow heating, could be quantified in consideration of these components. One must only think about that the calibrations described could be made only at “wind-off” conditions in the test section. Consequently, the vibrations of some optical parts, which could appear during the tests, were not taking into account. Although all external optical parts were mounted at a vibration-free area of the test hall that is decoupled through separate basis from the wind tunnel facility, the vibrations could cause additional energy losses. Furthermore, differences in supersonic free stream conditions comparing to those in calibration could have an influence to absorbed energy level.

The standard shadowgraph technique was used in these investigations to visualize the effect of optical pulsed energy deposition. The recording of shadowgrams was made by a high speed camera PHOTRON Ultima APX-RS 250K in this case with a constant frame rate of 30 kHz and an exposure time of 2 µs. The intensive electromagnetic radiation generated obviously by the discharge shows a strong interference with the function of the camera during the laser pulse that leads finally to a defect of the CMOS-chip at the beginning of the test phase. Only special measures undertaken subsequent on the camera housing with the aim to protect the chip from the damaging radiation could help to complete the investigations successfully. These measures, for example the installation of a grounded protection grid between the camera head and the lenses, influenced unfortunately the picture quality. The reason is that some parts of this grid positioned near the focal plane of the optical set-up work additionally as “Schlieren-knife”. The effect of this “knife” can be seen locally behind the bow shock wave on the pictures shown below.
Numerical technique

A numerical method described in details in [17, 18] is employed in the simulations. The code is based on a 2D axisymmetric formulation the Euler equations in conservative form and perfect gas model. A Godunov-type method is used, in which numerical fluxes at the current time level were obtained by solving a local one-dimensional Riemann problem by the HLLEM algorithm, third-order achieved using MUSCL reconstruction with min-mod limiter. The time integration is performed with explicit third-order Runge-Kutta TVD scheme. The energy for unit mass per unit time supplied by ED is modelled by a source term in the energy equation [18]. The grid size has 800x400 points, it was refined exponentially towards axis of symmetry. Accordingly to experimental estimations, an elliptical-shaped energy source with semiaxes of 1 mm and 0.2 mm in longitudinal and transversal directions correspondingly was chosen. Energy deposition time was set to 5 ns.

Results and discussions

Three experimental series were performed in order to investigate influence of different pulse parameters on the flow. In the first series the single discharge focus was fixed at the distance of 76 mm from the sphere, the energy was varied with values of 151, 264, 333, 548 and 666 mJ. The latter two values were achieved by double pulses with zero delay. The second series studied two subsequent pulses. Both pulses were focused at same distance of 76 mm, the energy for the first one was 333 mJ. The second pulse was emitted with delay of 20 µs and had reduced energy of 87 or 215 mJ. In the third series both pulses had equal energy of 333 mJ at the distances of 46 and 76 mm. The variable delays between pulses were 10 and 20 µs.

The numerical simulations were performed with described parameters, they are discussed together with experiment in the following subsections. Since in the experiment the camera start was not synchronized with laser pulse, the exact time of the first taken picture is unknown. Approximate time instant were derived from numerical simulations by visual comparison of the first computed and experimental picture. For this purpose positions of thermal spots and blast waves are matched. This technique is reliable since a good prediction of spot and blast wave evolution in time was shown in [17] by comparison with experiments. In accordance with described methodology the distance from body to laser discharge position was 74 mm, which is close to nominal value of 76 mm. Such a difference can be decreased if additional knowledge about geometry of the thermal source would be available. It should be noted that a good fit was achieved when the absorbed energy was twice as lower comparing to the given experimental values. This decrease could be explained by limitations of the numerical model which does not account real-gas effects and probably by mentioned losses in “wind-on” conditions.

Single pulse energy deposition

The experiments with single pulse underline the effect of energy level deposited into the flow at the fixed distance. An example of flow development in time is shown in Fig. 3 by experimental picture (left column) and predicted density gradient taken in a central vertical section of thermal spot (right column). It should be noted that density gradient in one section is only a rough approximation to experimental shadowgraph picture because a spatial averaging of density field is absent. A spherical blast wave around thermal spot upstream of blunt-body bow shock is seen in the photography (a) at 30 µs after the laser pulse. The blast wave hits the body at t=97 µs (b), the lens effect caused by spot / shock interaction is clearly visible at t=130 µs (c), after the interaction the spot is transformed into a tore-like structure (d, e), which penetrates downstream around the body (f). Generally with the energy level increased, the scales of flowfield specific structures grow. In the experiment for 151 mJ the most upstream bow shock position from the body was about 11.5 mm, for 333 mJ about 14 mm and for 666 mJ about 13.5 mm, the tore diameters were about 17, 19 and 23 mm respectively. The simulation results follow this trend, although the sizes are over predicted by 1-2 mm. The mentioned effect of energy level raise is demonstrated by pressure field in Fig. 4 before interaction at t=30 µs and during appearance of lens effect at t=130 µs.
Figure 3. Experimental flow shadowgraphs (left column) and calculated density gradients (right column) of a single pulse with energy 333 mJ.
The influence of deposed energy level is also visible from Fig. 5 where time-history of pressure in the stagnation point on the sphere normalized to that without discharge is shown. The annotated arrows correspond to the stages shown in Fig. 3 \((b, c, d)\). The pressure variation is higher with energy increased. The interaction differs from that observed at \(M = 3.45\), distance 25.4 mm and deposed energy of 283 mJ \([18]\), compare Fig. 5 and Fig. 6 (line 1). The first peak \(B\) caused by the blast wave impinge upon the sphere and last peak \(D\) occurred during further repeated interaction of reflected shock wave with sphere are present in both cases, while a local pressure increase \(C\) is absent in previous case. In accordance with performed additional calculation this local maximum disappears with distance decrease (Fig. 6, line 2). The region of pressure drop between peaks \(B\) and \(D\) appears during the stage of the lens effect and causes body drag decrease.

**Double pulse energy deposition**

A flow evolution with two subsequent pulses is shown in Fig. 7. The second impulse with reduced energy of 87 mJ and time delay 20 µs creates another thermal spot inside the first spherical blast wave \((a)\). The second blast wave is rather weak and during convection the spots change their shape \((b)\). The spot / blast wave structure before interaction differs from the single pulse significantly. However in the case of weaker second pulse presented in Fig. 7, the lens effect \((c, d)\) and tore development \((d-f)\) are similar to discussed case of single-pulse interaction, only small influence of second impulse to lens effect \((c)\) and tore diffusion \((e)\) can be identified (compare with Fig. 3). Also the simulation predicts this interaction rather good as well, but it tends to distinguish tore-like structures after interaction more clearly.

Such an agreement became worse with increasing energy level for the second pulse to 215 mJ and especially to 333 mJ (Fig. 8). A difference is observed during spots development before interaction \((b)\), where simulation predicts quite mentioned differences in spots structure, and in bigger bow shock displacement \((c, d)\), caused probably by different structure before interaction. In the experiment for the discussed case of time delay of 20 µs an influence of the subsequent impulse mainly expressed in diffusing of the tore structure after interaction, caused probably by turbulent mixing,
which is not accounted by employed numerical model. Another important problem is a correct prediction of spots interaction in the free stream. For this purpose the model for the source term in energy equation could be improved. Except real-gas effects which are not accounted by the numerical model, the assumptions done for derivation of employed source term [18] could be invalid. Unfortunately current experiment gives a little information for such an improvement.

The last series of double pulse experiment was aimed to investigate an influence of different distance and delay between the impulses. For this series with high energy level in both pulses (333 mJ) only some qualitative comparison could be done because the numerical prediction does not work well in this case. An influence of variable distance is illustrated in Fig. 9, where experimental and computed flow fields are shown at time instant of start the spot / bow shock interaction (the thermal spot only touches the shock) and at later time instant. In case of 46 mm distance, both blast waves are rather strong when the first blast wave impinges the body (a, b). With distance increase up to 76 mm, the spots are transformed toward a next stage of their evolution (c). Additionally they interact with the reflected blast waves of other intensity downstream of the bow shock. This leads to more pronounced lens effect in the first case (e, f). Thus, the simulation over predicts the lens effect (d, e) as in the previous case (Fig. 8).

The effect of time delay between the impulses is demonstrated in Fig. 10, where similar plot is made but with fixed distance of 76 mm and variable time delays 10 µs (a, b, d, e) and 20 µs (c, f). For the smaller delay the second blast wave disappeared to the time of interaction and thermal spots are joined together (a, b). In the experiment the interaction is quite similar for both delays (compare Fig. 10d and Fig. 8d), but simulation shows significant difference in size and structure (Fig. 10e, f).

Conclusions

The performed investigation highlights influence of various parameter on laser induced ED: distance, amount of energy and delay between subsequent impulses. The distance variation can lead to various flow pattern caused by combinations of impinging / reflected blast wave and thermal spot. As it was expected, the scales of interaction increased with higher energy. This trend also confirmed by increasing the energy of the second impulse in double pulse regime, while the overall influence is generally comparable in single and double cases for the same total deposited energy. The short delays discussed do not change the interaction much. Further improvements for the numerical model of source term are necessary for better prediction of spots interaction. Identified model sensitivity to the initial source shape, exposed itself on the long distances of spot / blast wave development.

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Figure 7. Experimental flow shadowgraphs (left column) and calculated density gradients (right column) of a double-pulse flow at distance of 76 mm with reduced energy of 87 mJ in the second impulse and 20 µs delay.
Figure 8. Experimental flow shadowgraphs (left column) and calculated density gradients (right column) of a double-pulse at distance of 76 mm with energy of both impulses equal to 333 mJ and 20 µs delay.
REFERENCES


Figure 9. Flow structure in double-pulse with energy of both pulses equal to 333 mJ and 20 µs delay at the start of spots / bow shock interaction (left column) and during lens effect (right column): a, d) experimental pictures for pulses distance 46 mm; b, e) corresponding pictures from simulation; c, f) simulation for pulse distance of 76 mm (for corresponding experimental pictures refer to Fig. 8c, d).
Figure 10. Flow structure in double-pulse interaction with 76 mm distance and energy of both pulses equal to 333 mJ at the start of spots / bow shock interaction (left column) and during lens effect (right column): a, d) experimental pictures for delay of 10 µs; b, e) corresponding pictures from simulation; c, f) simulation for delay of 20 µs (for corresponding experimental pictures refer to Fig. 8c, e).


