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UNSTEADINESS EFFECTS AT A PULSED-PERIODIC ENERGY SUPPLY TO SUPERSONIC FLOW

Vladimir N. Zudov Pavel K. Tretyakov and Andrey V. Tupikin

Khristianovich Institute of Theoretical and Applied Mechanics SB RAS
Institutskaya 4/1, 630090 Novosibirsk, Russia
Email: zudov@itam.nsc.ru

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Abstract. A gasdynamic structure arising in a supersonic flow around a heat source is experimentally and numerically studied. The heat supply was organized by activating breakdown plasma with focussed radiation from a CO2 laser operating in a pulsed-periodic mode. The repetition frequency of the pulses is found to have a profound influence on thermal-wake formation. It follows from an analysis of the aerodynamic drag variation at a flow with a thermal wake of the energy supply source around blunt bodies that the energy and pulse as well as its duration are the main parameters determining the efficiency of the frequency effect. The problem of the interaction of a shock arising from the counter-jet and the shock reflected from the plane with the contact discontinuity surface (the combustion front) was solved.

1. INTRODUCTION

During last ten years, a new research line in aerodynamics has been rapidly progressing related to exerting an intense active action on supersonic flows. Indicative of this are international conferences annually held in Norfolk (see[1,2]) and in Moscow (IHT RAS[3]). It is well known that under certain conditions even a weak local influence exerted on a flow may substantially change its hydrodynamic structure. Various types of local disturbances of the flows are possible introduced by heated wires[4], streamwise electric discharges[5], thin laser beams6, etc. A heat source in the form of a quasi-stationary plasma formation was first realized in sub- and supersonic argon flows[6, 7]. Stabilization of the heat supply in the range of velocities 190(430 m/sec was achieved using a pulsed optical breakdown initiated by a CO2-laser beam. To supply energy in a quasi-stationary manner, it is required that, during the time between two successive pulses, the plasma should suffer no substantial decay and not be carried away from the place of its activation by the gas flow. In subsequent studies[7,8,10-12], the conditions required for stabilization of such an optical discharge have been established, and both quantitative and qualitative information about the flow structure formed under such conditions was obtained. However, additional numerical studies seem to be necessary for gaining a better insight into observed phenomena and predicting them. To accomplish these goals, a system of two-dimensional non-stationary gasdynamics equations was used with different heat-source models.

2. PHYSICAL MODEL

When creating an optical discharge in supersonic flow a mechanism of the development is possible which depends on the conditions (the medium density and pressure) and the emission parameters (the emission power density): a rapid ionization wave (RIW, D_F = 20–100 km/s, D_F is the velocity of the absorption front propagation); the light-detonation wave (LDW, D_F = 3–10 km/s); the radiation wave (RW, D_F = 10–40 km/s); the disruption wave[7]. In the case of the light-detonation wave, the threshold energy amounts to $J \sim 10^7$ W/cm^2 for the argon flow. And as was shown in paper[8], such a regime realizes under a pulsed-periodic supply of the laser emission. For flows with velocities of 400÷600 m/s and the frequencies of sequences of laser pulses f =10–100 kHz the energy release per pulse may be assumed to be "instantaneous" because the LDW velocity exceeds the flow velocity by more than an order of magnitude. That is an "instantaneous" energy release occurs in the flow in a cylindrical region of a given size. An elliptic shape of disturbances waves emanating from the energy release region may be considered as a confirmation of this (Fig. 1).

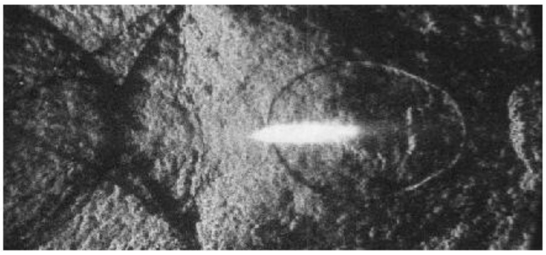


Figure1. Optical discharge in supersonic flow (M=2.0, d=20mm, f=50 kHz)

The observed transverse size is about 1 mm for the focusing diameter of 0.2 mm. The longitudinal size (the length) depends on the pulse duration and power density in the focusing plane.

Basing on the assumption on the light-detonation regime of the optical discharge development one can determine the propagation velocity of the absorption front towards the ray $D=[2(\gamma^2-1)J/\rho]^{1/3}$. ($\rho$ is the medium density, γ is the adiabatic exponent)

The variation of power density $J(t)$ is determined from the power dynamics of the laser pulse $W(t)$ registered in experiment and the known area of the ray section. At a high duration or high energy parameters of the pulse a considerable variation of the power density may be due to a shift of the LDW front from the focal plane, where the ray area is minimum. Due to a power dependence (with exponent 1/3 < 1) of the velocity on the power density the influence of above factors at the computation of L becomes appreciable only for fairly strong variations of corresponding parameters. The section area for a ray focused along the z axis is $s(z) = s_0\{1+(\lambda z/\pi d_0^2)^2\}$, where d_0 is the focusing spot diameter, s_0 is its area, and λ is the emission wave length. For our case, λ = 10.6 µm, d_0 = 0.2 mm. By the definition $D = dz/dt$, we have following:

$$dz/dt=\{2(\gamma^2-1)W(t)/s(z)\rho\}^{1/3} \quad (1)$$

By separation of variables, this expression may be reduced to the integral form:

$$[2(\gamma^2-1)/\rho]^{1/3}\int_0^{\tau} W(t)^{1/3}dt = \int_0^{L} s(z)^{1/3}dz \quad (2)$$

Transferring the constants from the integrals and collecting them on the left-hand side, we obtain:

$$[2(\gamma^2-1)W_0/s_0\rho]^{1/3}\int_0^{\tau}\bar{W}(t)^{1/3}dt=\int_0^{L}\bar{s}(z)^{1/3}dz$$
, or

$$V_0\int_0^{\tau}\bar{W}(t)^{1/3}dt=\int_0^{L}\bar{s}(z)^{1/3}dz \qquad (3)$$

Equation (3) couples the heat-source extension L with the wave propagation time τ (W_0 is the quantity scale for W in the graphs of Fig. 2).

The integration on the right-hand side within the limits of L = 5−10 mm (the range of experimentally observed sizes of the heat source) showed a small deviation of the results from original values of L (less than 5 %). This points to a low manifestation of the expansion effect of the light channel at the determination of the heat source sizes, although the source limiting area differs from the focusing spot by a factor of nearly 1.5.

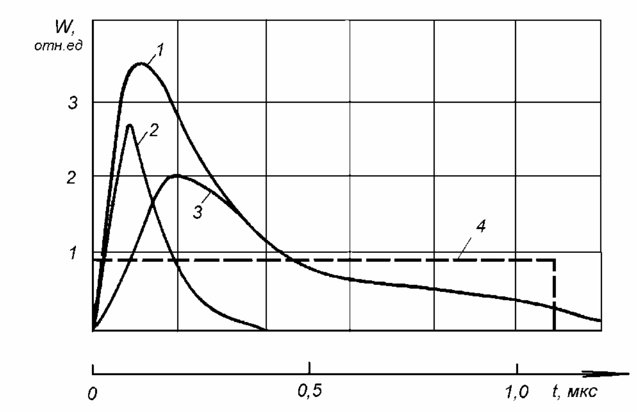


Figure 2. CO_2-laser radiation pulse signal
1 – original; 2 – passed through optical discharge; 3 – absorbed by gas; 4 – efficient

Besides, One can use as the LDW propagation velocity the time-averaged value (D_m in the following), which depends on the pulse duration and the energy therein.

Thus, assuming that the absorption zone length is $L=\int_0^{\tau}Ddt=D_m\tau$, taking into account the fact that a shift from the focusing zone does not lead to a considerable variation of the power density, and assuming also the pulse duration constancy $\tau \approx 1.1$ μs (Fig. 2), we have performed the estimations. Table I summarizes the estimation results for the regimes with different frequencies of pulse sequence and the pulse energy.

f, kHz	W_{lim}, kW	E, mJ	D_m, km/s	$J_{ef}\times10^{12}$, W/m^2	L, mm
100	1.6	16	5.7	0.48	6.3
45	1.8	40	7.7	1.2	8.5
25	1.45	58	8.7	1.7	9.6
12.5	1.35	113	11	3.4	12

Table I

The pulse duration was indeed no constant quantity in experiment, it varied with frequency. If there was no disc change on the modulator at frequency change, then $\tau_1/\tau_2=f_2/f_1$. Otherwise $\tau = (1/f)*1/n$, where n is the on-off time ratio.

The length L depends linearly on the pulse duration. On the other hand, at the determination of conditions for the passage to a quasi-steady regime of heat release, no high accuracy of determining the given quantity was required because the matter concerned mainly the orders of magnitude of the quantities.

3. MATHEMATICAL MODEL

It was assumed in computations that a uniform supersonic flow of monatomic gas with the constant ratio of specific heats γ=5/3 impinges onto the energy source. The following geometric parameters of the energy source are taken: the length 8.5 mm, radius 1 mm. The energy source forebody was located at point with coordinates x=0, y=0. It was found in experiments with a pulsed-periodic laser that the energy source has an extended shape, therefore, it was assumed that the energy absorbed by the medium is approximately constant in each pulse, and the shape of the energy release region is close to the cylindrical one. It was also assumed in accordance with experiment that the energy absorbed by the medium in one pulse is E = 0.04 J (the frequency f = 45 kHz). The value of E was constant in all computations. The specific energy absorbed by the medium unit mass per unit time equals e = E/(m*t), where m is the mass to which the energy is supplied, and t is the energy release time. For experiment conditions, t=1 μs, and the period T equals 22.2 μs for frequency 45 kHz and 10 μs for f=100 kHz. The source is switched on at the beginning of each period T per time t, and, therefore, its power alters periodically with time. A supercritical regime of energy supply corresponds to chosen conditions. In this case, the zones a subsonic flow, which pulsate with time, arise in the flow.

4. GENERAL PECULIARITIES OF THE FLOW IN THE ENERGY SUPPLY REGION AND DOWNSTREAM OF IT.

During the initial period of time at the formation of the radiation pulse, strong gas flows arise in the energy supply region, which are directed from the center of this region. The jets with velocities exceeding considerably the freestream velocity form to the left and to the right of the middle. The obtained results are similar to the flow pattern at a volumetric explosion.

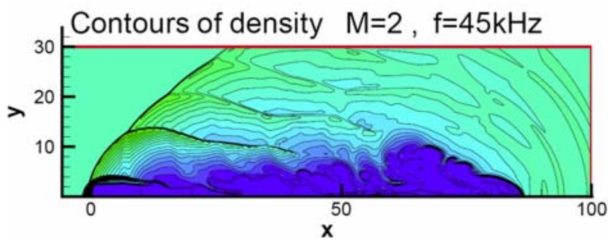


Figure 3. Contour of density.

The jet directed oppositely to the free stream serves a peculiar piston ahead of which a shock wave arises. The shape of this shock wave resembles a shock wave arising ahead of a blunt body in a supersonic gas flow around it. Depending on the energy supply intensity, both the regions of completely supersonic flow and the regions of subsonic flow may arise behind the shock wave. The thermal spots begin to interact with one another with time depending on frequency or shift downstream independently from one another. The quasi-steady flow regime starts at a frequency of 45 kHz. The time of the formation of this regime is fairly short, of the order of 4-5 pulses. These pulses are enough to form a quasi-steady pattern with the presence of an envelope of shock waves from pulses. The region, to which the radiation energy was supplied, expands with time. There is a very sharp difference between this region and the remaining flow. It follows from computations for M= 2 that the transverse sizes of the region with energy supply increase with time and amount to about 4 - 6 radii of the heat source, Fig.3. This is close to the value observed in experiments. The zones with reverse flows arose at the interaction o two neighboring regions with energy supply (M=2). These zones vanished with increasing Mach number.

5. NUMERICAL MODELING OF THE ENERGY SOURCE INTERACTION WITH A CONE.

An axisymmetric pulsed-periodic energy source lies in a supersonic flow with the Mach number 2. The energy source has the following geometric dimensions: its length equals 8.5 mm, and its height is 1 mm. The energy source starts at the coordinate origin (x=0). The freestream parameters: the pressure P=56 kPa; the temperature 130 K. The energy release time is 10^{-6} sec. The computations were carried out at the frequency of 12 - 100 kHz of the repetition of pulses. The energy supplied in a single pulse equals 0.04 J. The cone radius is 3 mm. The cone semi-apex angle equals 30 degrees. The freestream gas is assumed to be the argon with the adiabatic exponent γ=1.666. At first the energy source and the wake of it form. That is a wake forms downstream of the energy release region, and a shock wave forms ahead of it and around it. The process under study has an intrinsically unsteady character. This is confirmed by a flow structure abruptly changing in time. The new shock waves arise periodically around the energy release region in the flow, which interact with the shock waves generated earlier, Fig4.

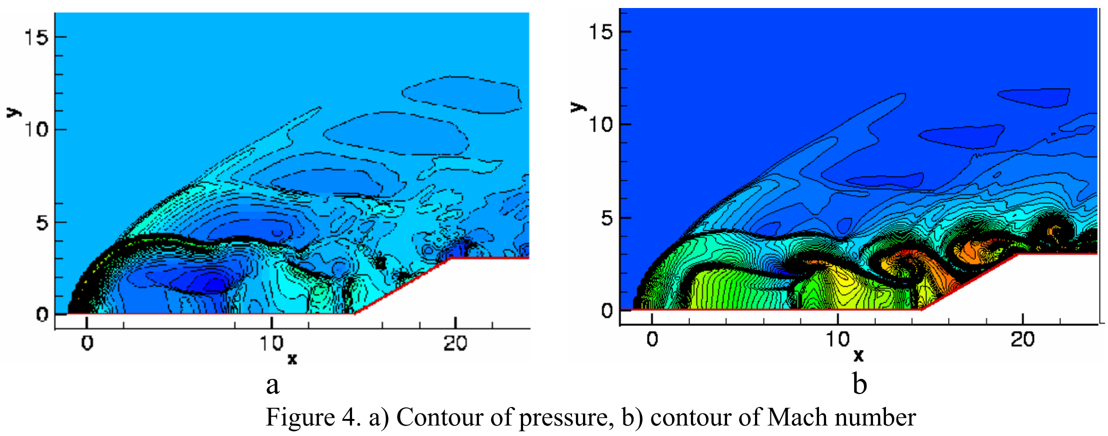
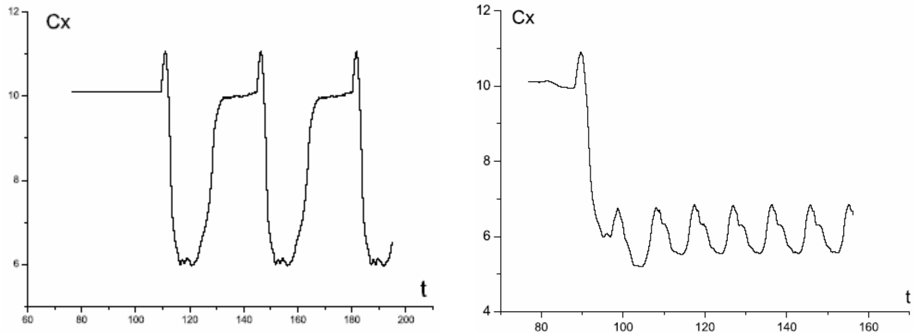


Figure 4. a) Contour of pressure, b) contour of Mach number

The pulsed-periodic formation of shock waves leads to a very strong temporal dependence of the forces acting on the cone. The force acting on the model has at first a purely unsteady character. However, after some (rather short) time the temporal dependence of the force has a pronounced periodic character. Thus, the flow has a quasi-steady character. The mean force acting on the cone was computed in the work. This force was found in the quasi-steady interval, and the averaging was carried out over 8-10 periods.

In the figure showing the flow structure one can see the formed shock-wave structures, which were formed in the flow during the dozens of pulses.



a b

Figure 5. Instantaneous force. a) 12.5 kHz, b) 45 kHz

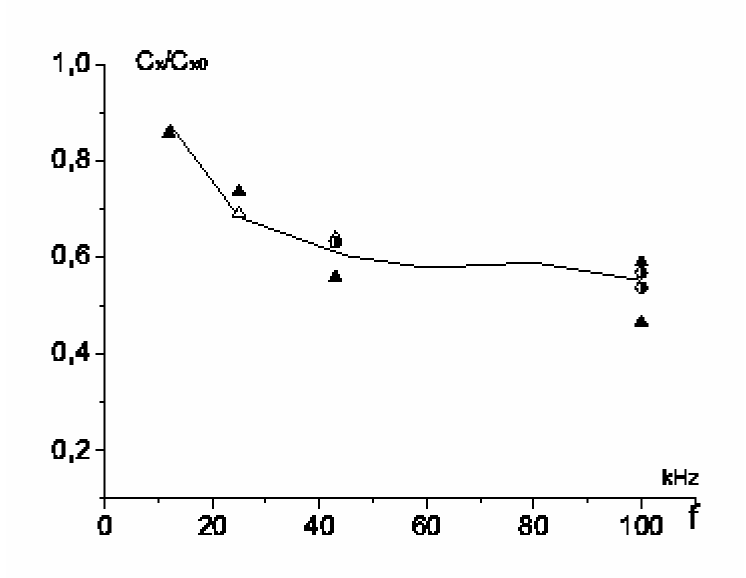


Figure 6. Average force. Experiment data (Tretyakov P.K. et al[8,10,12])

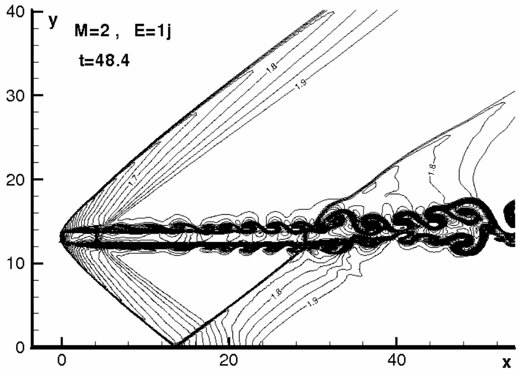
The influence of pulses frequency on the flow structure was elucidated. The data for computation were taken from the experiment.

6. NUMERICAL MODELING OF THE INTERACTION OF AN INCIDENT SHOCK WAVE WITH THE WAKE OF A PULSED-PERIODIC ENERGY SOURCE.

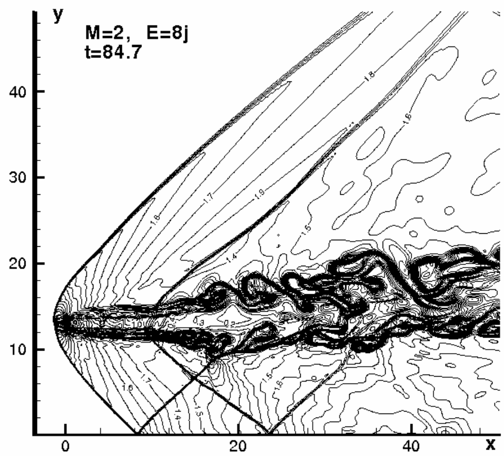
The problems of unsteady propagation of shock waves and aeroacoustic disturbances in continua, which arise in various domains of scientific research, are extraordinarily complex for their modeling — both for the numerical and experimental modeling. The processes occurring in the flows around bodies affected by a pulsed-periodic energy supply from an external source may serve as an example. The efficiency of control depends on the unsteady flow structure[10-12]. The complexity of experiments does not enable to watch the development of a wake of the heat release source. Therefore, the use of mathematical modeling appears to be necessary for understanding and prediction of observed phenomena. The application of a pulsed-periodic energy contribution to the flow for stabilization and increasing the efficiency of the processes of fuels combustion may be another possible application[10-12]. In this case, the energy release source initiates the subsequent development of the flame front.

The considered problems are similar to a certain extent because in the both cases, a heat source localized in the given place and a wake of it developing in time forms in the flow. Since the wake as was shown previously[10-12] is a narrow but rather extended region with the gas-dynamic parameters strongly differing from the free stream. Therefore, at the use of such wakes in gas-dynamic applications, a problem of the interaction of an unsteady wake with the external disturbance arises. The external disturbance may be weak and strong. The compression and expansion waves are usually considered as a weak disturbance. The shock wave is a strong disturbance in supersonic flow. Two variants of the external disturbance interaction with the wake are possible. The first one is as follows: a steady shock wave exists in supersonic flow, and the formation of a localized unsteady energy source starts ahead of it. A rather extended wake forms behind the localized energy source, which starts interacting with the shock wave. Another variant: there is a pulsed-periodic localized energy source in a supersonic flow. Behind this source, there is an extended wake. Then at some moment of time, a shock wave generated in some way arises in the flow. This shock wave starts interacting with the pulsating wake of the localized unsteady energy source.

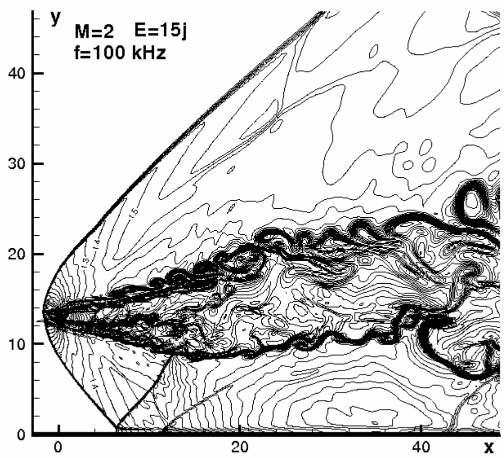
In the given work, the regime of strong interaction is considered, when a wake is at first formed from an energy source placed in supersonic flow, and then a shock wave impinges on this wake. Thus, a problem of the unsteady interaction of the shock wave with a wake from a pulsed-periodic localized energy source is considered. The difference of the proposed study from other works consists of the fact that, first, the main attention is paid to the formation and development of the structure of a wake of the energy release source, second, the influence of the supplied energy on the regimes of wake interaction with a shock wave incident on it was investigated, third, the Godunov's method was further developed for such a class of problems. In a supersonic flow with the Mach number 2, there is a pulsed-periodic energy source above the surface. The energy source has the following geometric dimensions: its length equals 8 cm, and the height is 2 cm. The energy release time is 10^{-6} sec. The frequency of pulses repetition equals 100 kHz. The energy supplied during a single pulse to the identified mass equals 1 - 15 J. It is clear from the problem formulation that at first a wake of the energy source is formed, and then a shock impinges on the wake. The surface onto which impinged the bow shock wave formed by the energy source served the shock wave generator. That is a wake forms behind the energy release region, and a shock wave forms ahead of it. The process under consideration has an intrinsically unsteady character. The shock wave formed ahead of the energy source impinges onto the surface and is reflected also by the shock wave. Depending on the intensity of the energy source a wake with a different Mach number may form downstream of it, Fig.7. At some distance from the energy release region it may be transonic or subsonic on the average over the section. Depending on the wake type different regimes of the incident shock wave interaction with the wake of energy source may form. The computations resulted in the following: if the incident shock wave interacts with a subsonic wake, then it reflects from it by an expansion fan; if the incident shock wave interacts with a transonic wake, then it passes through the wake. In the place of a transition from transonic flow to the subsonic flow (in the wake) two shock waves form on the wake external surface. One of them is on top, another lies below. The regimes of the incidence-reflection of the lower shock wave from the surface and from the wake subsonic part are seen in the Fig.7c.


M=2 , E=1j
t=48.4
y
x
0
10
20
30
40

a


M=2, E=8j
t=84.7
y
x
0
10
20
30
40

b


M=2 E=15j
f=100 kHz
y
x
0
10
20
30
40

c

Figure 7.

7. CONCLUSIONS

The microwave (laser and/or ultra-high-frequency) emission energy may be applied for creating the heat sources in supersonic flow. The frequency and power of energy pulses determine the thermal wake properties.

The pulsed-periodic heat supply from external energy sources may be efficient for lowering the aerodynamic drag, the “sonic” boom intensity, and flight control.

The sonic boom weakening occurs at the expense of the interaction of a shock wave arising from the wing with the thermal wake.

At the positioning of heat sources near the surface one can use the peculiarities of the thermal wake with the surface for controlling the lift force. The lift-to-drag ratio of the wing can be varied by shifting the heat source location and varying the source power.

8. REFERENCES

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