SHIELDING OF A SPHERE FROM A SHOCK WAVE IMPACT

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An energy release near flowing body changes the supersonic gas flow structure and reduces the body resistance [1]. Behind a strong shock wave the flow is also supersonic one. Therefore a heat deposition near a body is expected to reduce a force impact of a strong shock wave.

A strong wave reflection from a cline is studied experimental and numerically in [2] under electric arc discharge about the cline surface. If the discharge is absent, then the reflection is shown to be regular or irregular one depending on the cline angle and the incident wave Mach number. There is a critical cline angle. Over it transition changes the interaction regime.

Arc discharge presence leads to reflection picture reconstruction. For example, if the cline angle is closed to critical one, regular reflection transforms to Mach interaction structure, which existences long past the arc discharge turning-off. Obtained in [2] experimental and theoretical results are closed both a flow structures and main quantitative parameters.

Problem definition and solution method

In this paper a strong incident shock wave reflection from a sphere under energy release in front of this sphere is studied numerically. Two dimension Eiler's equations are applied base of mathematical model. The energy deposition is modeling by an additional term in the energy equation.

In polar coordinate system these equations have the form

$$\frac{\partial \rho y r}{\partial t} + \frac{\partial \rho y u r}{\partial r} + \frac{\partial \rho y v}{\partial \theta} = 0,$$

$$\frac{\partial \rho y r u}{\partial t} + \frac{\partial y r\left(p + \rho u^2\right)}{\partial r} + \frac{\partial \rho y u v}{\partial \theta} = \\ = \left(p + \rho v^2\right) + \vartheta p r \sin\theta,$$

$$\frac{\partial \rho y r v}{\partial t} + \frac{\partial \rho y u r v}{\partial r} + \frac{\partial y\left(p + \rho v^2\right)}{\partial \theta} = \\ = -\rho y u v + \vartheta p r \cos\theta,$$

$$\frac{\partial \rho y r\left(H - p/\rho\right)}{\partial t} + \frac{\partial \rho y u r H}{\partial r} + \frac{\partial \rho y v H}{\partial \theta} = \\ = \rho y r \dot{E}(t, r, \theta),$$

$$H = \frac{\gamma}{(\gamma - 1)} \frac{p}{\rho} + \frac{(u^2 + v^2)}{2},$$
$$y = r\sin(\theta), \quad \vartheta = 1.$$

Traditional table of symbols are used here for gas dynamics parameters. If a distance between the wave and the spherical body equals to the sphere radius, the energy release rate $\dot{E}$ isn't equal to zero and is constant and uniform. The heat release intensity may be characterized by the relation of the energy $q = \dot{E}t_0$ deposited during specific time t_0 to full mass unit energy of the gas flow behind the incident shock wave $E_f = (\gamma - 1)^{-1} p/\rho + u^2/2$.

Calculations are made on the base of the conservative first order of accuracy numerical Godunov's scheme [3] with used a moving grid. The mobile calculation domain boundary is connected with sonic and reflected waves. The calculating region is also limited by the sphere surface and axis of symmetry 'X' in the line of the incident wave motion.

Features of a strong shock wave interaction with a sphere over a heat shield

If a heat release is absent, the problem solution in dimensionless values is defined by a shock wave Mach number M_w and a specific heat ratio γ only. Below it is considered calculation results for $M_w = 3$ and $\gamma = 1.4$. Behind the shock wave the flow is supersonic one with Mach number $M_f = 1.433$. Initial regular reflection transforms to Mach configuration when a leading interaction point moves along the sphere surface contour. The triple point moves away from the sphere. At the same time the arched "Mach leg" skirts the sphere contour and reflects from the axis of symmetry. A new triple point arises behind the spherical obstacle. It moves together with the shock wave and slowly moves away from the axis of symmetry. In time the flow near by sphere becomes a stable one. It looks like a steady supersonic flow around a sphere. In front of the

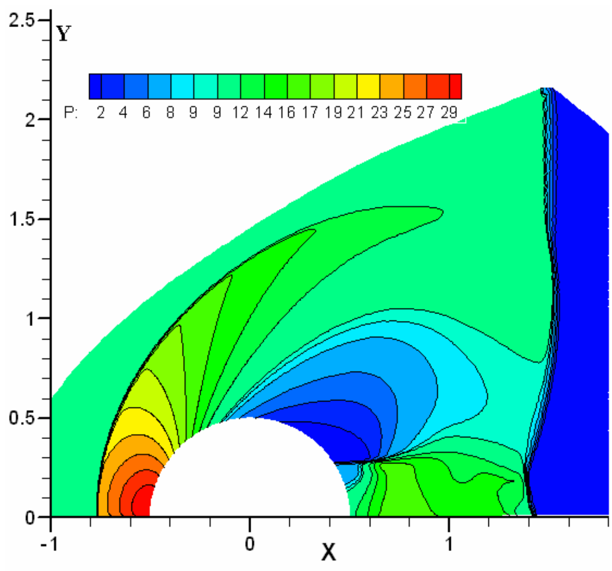

Fig.1. Isobars, q=0.

sphere there is arisen reflected shock wave (fig. 1). At the sphere leeward the flow accelerated to supersonic velocity is limited by a local shock wave. Behind this wave is a returned flow zone.

If an energy deposition is taken into account, the relation q/E_f and dimensionless geometry parameters of a heat release domain extend the defining parameter list. A spherical body diameter is assumed to be equal to the unit $(2R = 1)$, the specific time $t_0 = 2R/\sqrt{p_0/\rho_0}$. Here p_0 and ρ_0 are the pressure and the density of a rest gas.

Below three kinds of the energy deposition cavities are considered. The first can be obtained by revolving of a ring segment around the span on the axis of symmetry just in front of a sphere. This span length equals the spherical body radius. The cavity volume is defined by formative arch value 2φ.

If $\varphi = \pi/2$ the energy release domain is the sphere with diameter d=R. From the beginning the incident shock wave interacts with perturbed cavity. This interaction generates reflected and through-passing shock waves. They have a common triple point A on the end of rectilinear part of incident shock wave. The reflected wave moves off the cavity not far and

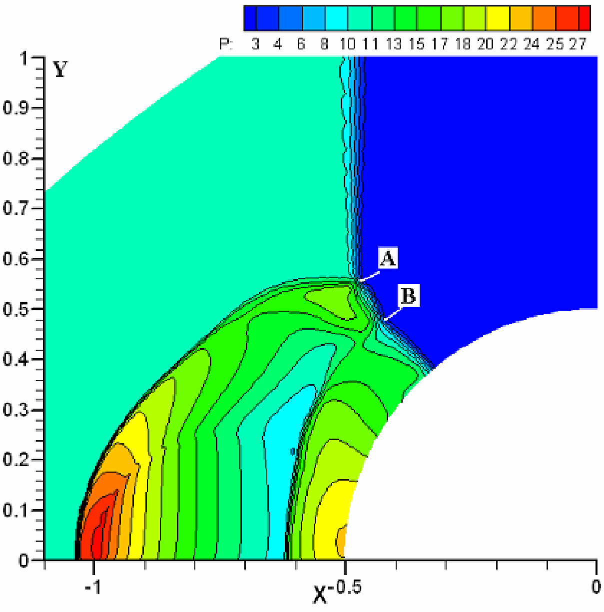

Fig. 2. Isobars, φ = π/2, q=20E$_f$

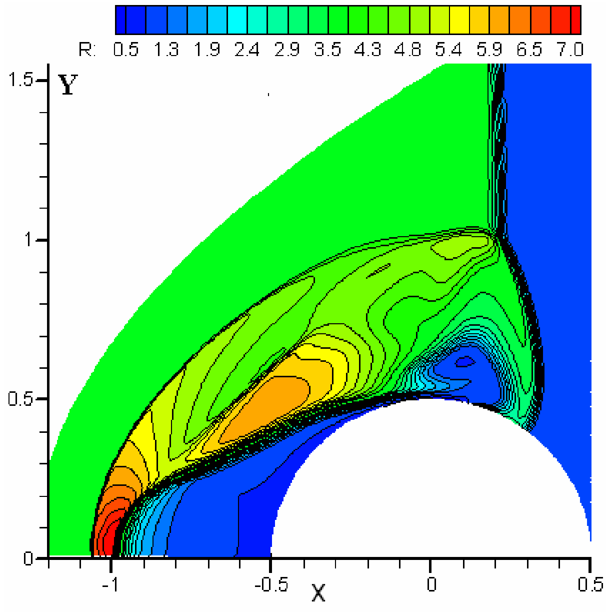

Fig. 3. Isochors, φ = π/2, q=20E$_f$.

practically comes to a stop. In heated gas the passing wave has a higher velocity. It decreases the intersection angle between the arched "Mach leg" and rectilinear part of incident shock wave. Their interaction becomes an irregular one with a second triple point B (fig. 2).

At the same time the "Mach leg" prominent to motion direction begins to interact with the spherical body. An inner reflected wave arising due to this interaction moves against to the main gas flow and runs into the first reflected wave in the course of time. At the sphere the regular reflection of passing "Mach leg" transforms to the irregular one with already existent triple point B. The "Mach leg" motion along sphere contour increases its incline angle to the rectilinear incident wave. Therefore, in contrast to a cline [2], the point B comes close to A and merges into A in time.

The irregular Mach configuration with one triple point, specific for any energy deposition absence, is rebuilt at the moment, when the "Mach leg" is else on the sphere contour. The shock wave entrains a part of the heated gas from energy deposition cavity (fig. 3). The sphere falls into a low gas density domain.

Analogical interaction picture is observed under φ = π/3, but the low gas density domain contained the sphere is more thin. Reflected wave doesn't practically depart from the forward edge of the energy release cavity.

If the energy deposition cavity is thinner (φ = π/6 и π/4), many features of the interaction dynamics remain real. But in this case, the

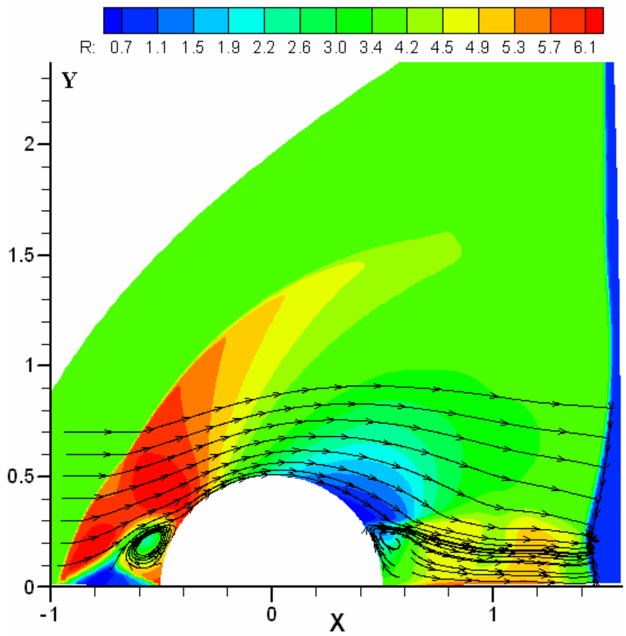

Fig. 4. Constant Mach number lines, φ = π/6, q=340E$_f$.

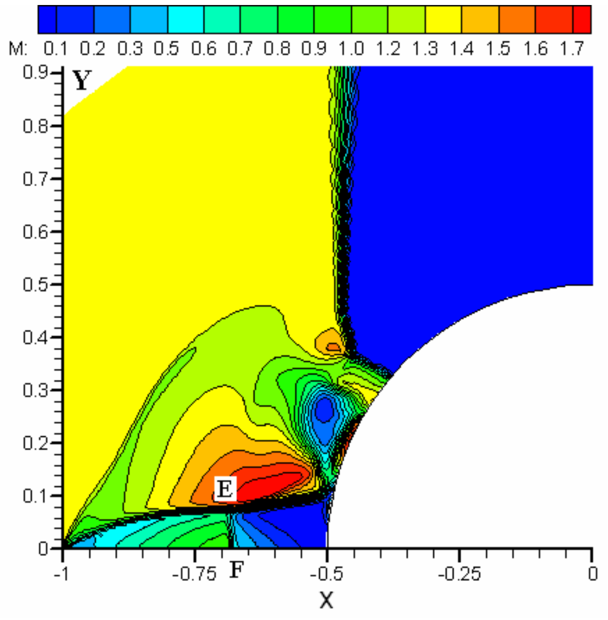

Fig. 5. Flow lines on the gas density field, φ = π/6, q=20E_f

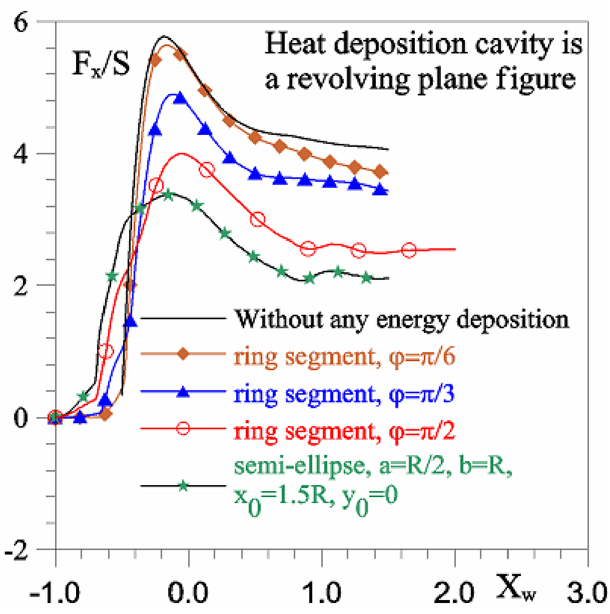

Fig. 6. Lengthwise force divided by the sphere surface area, q=20E_f

gas heated in an energy deposition cavity doesn't move around the sphere. It remains in front of the spherical obstacle. The main flow envelops the energy release cavity and generates a circulating zone (fig. 4). This zone is absent, if φ = π/2 or π/3.

Detail interaction description needs in a lot of illustrations. Fig. 5, for example, fixes the EF inner reflected wave propagation through the heated gas cavity like in a waveguide. After that a new shock wave gets off this cavity and arrives at the external reflected wave. Finally, the external reflected shock wave may be presented as composed by two lengths: the lower part is a result of the incident wave interaction with the energy deposition cavity and the second part is the shock wave reflected direct from a spherical body.

Efficiency of a heat shielding of a sphere from a shock wave impact

In Fig. 6 the force impact on the sphere is presented as the time function for different angles φ under constant heat release intensity q=10.2E_f. The abscissa indicates the incident shock wave location. The lengthwise force maximum decreasing corresponds to the maximal volume in this cavity family (φ = π/2), i.e. in the spherical cavity case. This cavity diameter is equal to the spherical body radius d = R.

The cavity collection expansion by spheroids with the lengthwise axis 2a = R and the cross axis b > R/2 decreases the force impact still more (fig. 6).

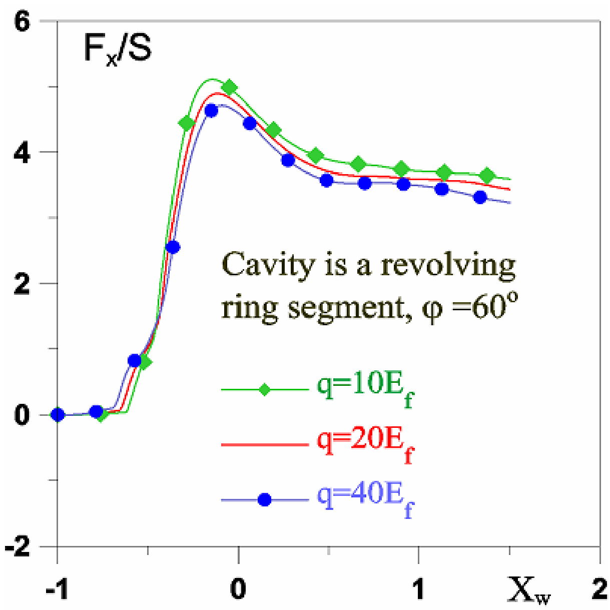

Fig. 7

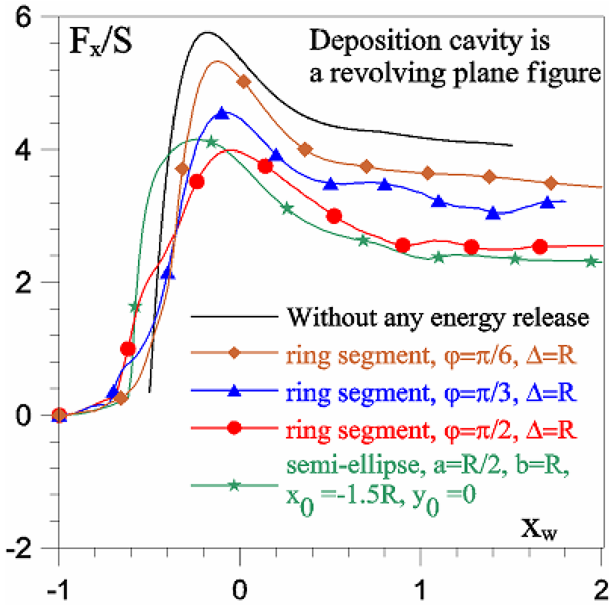

Fig. 8

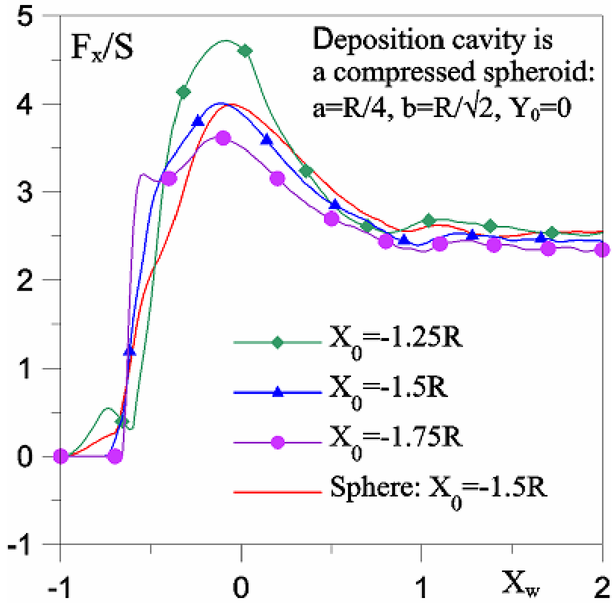

Fig.9.

So, the cavity volume raising reduces a lengthwise force impact of an incident shock wave on a spherical obstacle.

The energy intensity increase has a weak influence on the force impact (fig. 7).

Obtained above results show that it is interesting to consider different geometry cavities under a constant total energy release. More exactly, under a constant value of the composition $q \cdot V = 20 E_f \pi R^3 / 6$.

In Fig.8 calculation results for the expanded cavity collection considered above are presented. The spherical cavity is obviously most effective.

Ellipsoid cavities can be supplement with spheroids compressed and removed along the abscissa axis. It is the second cavity collection.

Fig. 9 presents the effectiveness of ellipsoids, the lengthwise axis is in four times less then sphere radius 2a=d/2=R/4. They are at different distance from spherical body (from zero to d/2). In Fig.9 the value X_0 is the spheroid center abscissa. Most remote ellipsoid is the best. But the lengthwise force integral approximately is equal to the integral for spherical energy release cavity.

Further ellipsoid compression and remove towards incident flow in defined limits leads to the force impact rise (fig. 10).

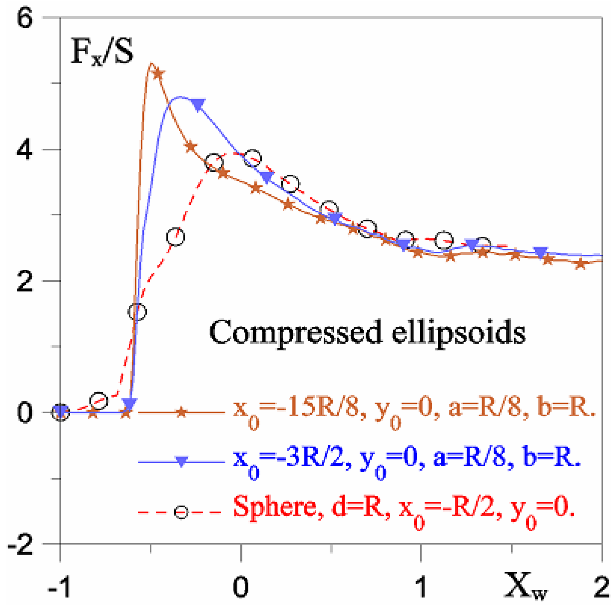

Fig. 10

Third and last kind of heat shield configurations consists of semi-spheroids directed towards incident wave. They involve half of a spherical body. These spheroids and the body have the same center. The spheroid cross axis equals the body diameter (2b=2R). If the spheroid lengthwise axis is some longer, than the body diameter (a>1.25R), the heat release does not practically influence on the lengthwise force maximum, but decreases its value after the incident wave passes over the sphere top (fig.11). The maximal thickness shield (a=2R) has the effectiveness like the spherical cavity with diameter d=R.

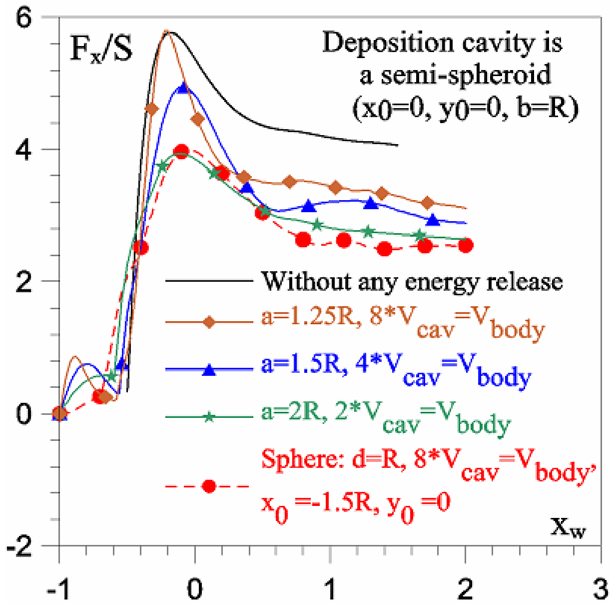

Fig. 11

Conclusions

An energy release in front of a protected sphere changes a structure of a strong incident shock wave interaction with the object. Regular to irregular interaction transition takes place at more early interaction stage. Structures with two triple points are arisen. Under a heat deposition rate is constant a flow near by sphere becomes stable in course of time. Its structure gets features, which are specific for a supersonic flow in front of a sphere under the energy deposition [1]. There are separated region and a circulating zone in dependence on energy release conditions.

The flow accelerated to supersonic velocity at the sphere leeward is limited by a local shock wave. Behind this wave there is a return flow zone. A shock wave reflection from the symmetry axis is irregular behind the spherical obstacle. The triple point moves coupled with the incident wave and slowly steps aside from the axis of symmetry.

A heat deposition growth leads to weakening of the lengthwise force impact on a sphere, especially due to increasing of the heat release cavity volume. Under considered assumptions about the cavity size and geometry the lengthwise force impact can be twice reduced. A spherical cavity is one of the best for energy release.

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