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The supersonic shock wave interaction with low-density gas bubble

B. Rybakin [a,*], V. Goryachev [b]

[a] SRISA RAS, Moscow, Russia
[b] Department of Mathematics, TSTU, Tver, Russia

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ABSTRACT

Results of computer modeling of the process of shock wave interaction with low-density gas bubble are presented in the current work. Deformation and instability formation are being modeled by a high-order-accurate scheme of TVD type. Calculated area is presented by parallelepiped, the number of calculated area cells along axes X, Y and Z is equal to $4096 \times 1024 \times 1024$. The calculated area is filled by air, one bubble has radius equal to 128 cells of the calculated area and is filled with low-density gas.

1. Introduction

This paper presents computer modeling results of shock wave interaction with low-density gas bubble. Modeling is carried out in a three-dimensional Cartesian coordinate system. For thorough investigation of arising flow we use a detailed grid with dimensions equal to $4096 \times 1024 \times 1024$. The Mach number in falling wave had been changing from 2.5 to 3.0, the Atwood number is $At = 0.9334$. Interest to such investigations is caused by many factors. With the purpose of engines creation for prospective hypersonic devices it is necessary to study in detail processes of turbulent hashing of fuel components with an oxidizer [1]. In astrophysics, problems often arise concerning interaction of shock waves, being formed as a result of supernova explosions and relativistic emissions, with molecular clouds of interstellar and intergalactic substances [2]. As a result of such interactions, fragmentation and collapse of molecular clouds happen, which lead to new sidereal and planetary systems formation.

The study of collapse of gas bubbles found in liquid is very actual for lithotripsy—removing kidney stones without surgery. With the view of machinery creation for removing kidney stones without surgery it is necessary to find optimal dimensions of bubbles, safe level of falling shock wave [3]. For this purpose it is necessary the high-resolution study of deformation and collapse of bubbles which must lead to stones destruction, but not to injure surrounding tissues.

Computer modeling of the process of shock wave interaction with gas bubble had been studying by different authors [4,5]. Formation of multiple vortical rings had been found out. In [6] there had been carried out the three-dimensional high-resolution numerical modeling for interaction problems “bubble–shock wave”. Effects of turbulence and non-axial symmetry had been registered.

The interaction of shock wave with division boundaries of gas with different densities leads to arising Richtmyer–Meshkov instabilities, and then to turbulent hashing arising. Such a process allows improving the oxidizer mixing with fuel in engines combustion chamber [7]. The plane shock wave passing through curvilinear surfaces which divide substances with different densities gives rise to a baroclinic effect related to difference between pressure and density gradients [8,9].

The experimental investigations had been carried out by different authors [6,10,11] on behavior of these instabilities at the boundary of two environments division. It was

* Corresponding author. Tel.: +7 91 6320 8459.
E-mail addresses: rybakin1@mail.ru, rybakin@vip.niisi.ru (B. Rybakin).

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registered that at boundaries there had been observed deformation and processes instability of cylindrical and spherical bubbles interaction. Despite that the majority of work on numerical modeling was carried out in two-dimensional statement and not with high resolution. Nevertheless, it allowed understanding some questions concerning interaction of shock waves of different intensities and low-density bubbles.

However, instability of these processes, strong nonlinearity and complexity of arising flow structure lead to the necessity of carrying out three-dimensional calculations on a detailed grid. Moreover, to study flow subtle peculiarities it is necessary to use high resolution visualization programs. For visualization of such complex non-stationary three-dimensional flows it is necessary to use graphic processors powerful enough.

2. Governing equations

Calculated area is presented by a parallelepiped of size equal to $4096 \times 1024 \times 1024$ of cells along axes X, Y and Z respectively. In calculations the cells $\Delta x, \Delta y, \Delta z$ are set of equal sizes: $\Delta x = \Delta y = \Delta z$. Percussion interaction with bubble of gas is related to the shock wave passing through gas which has another thermodynamic characteristics. Moreover, by modeling such interactions, we make a number of other simplifications. Real shock wave has finite thickness, its surface is not perfectly plane, equations of state for gas in ambient area and in bubble are different. The discrepancy is in different values of molecular mass and ratio of heat capacities γ. Thus, each gas has its own sound velocity equal to $a_i = \sqrt{\gamma_i p_i/\rho_i}$, i=0, 1 (i=0 for ambient gas, i=1 for bubble). The Mach numbers $M_i = u_i/a_i$ for these environments will also differ. However, it is shown in [4,13] that one can disregard the discrepancy in thermodynamic characteristics of different gases and inequality of rates γ and to use model with one rate $\gamma = 1.4$.

We will disregard these discrepancies in the presented work. We will assume that the quantities given above are equal both in the ambient gas and in the bubble. We will study the problem of shock wave interaction with gas bubble in a Cartesian rectangular coordinate system. Euler schemes work well in the majority of problems of gas dynamics. They have some peculiar limitations related to the possibility of arising non-physical oscillations at edges of the shock waves and at the division boundaries of gases with different densities. Moreover, it is difficult to make calculations for gases which are in the same cell, but have different gas-dynamic parameters.

Lagrangian coordinate systems devoid of these limitations, but they have their own problems which arise when large deformations appear. That is why the majority of computing problems, especially in multi-dimensional setting, are based on a Eulerian coordinate system.

We will consider non-stationary flows of ideal compressed gas. Also we will disregard the effects of viscosity and friction. Then system of mass conservation laws, and of amount of motion and energy in the three-dimensional Cartesian coordinate system can be written in the following way:

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}(\mathbf{U})}{\partial x}+\frac{\partial \mathbf{G}(\mathbf{U})}{\partial y}+\frac{\partial \mathbf{H}(\mathbf{U})}{\partial x}=0 \tag{1}$$

here vector of conservative variables looks like: $\mathbf{U} = (\rho, \rho u, \rho v, \rho w, \rho e)^T$. Vectors of flows will be given as the following:

$$\mathbf{F}(\mathbf{U}) = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ \rho u w \\ \rho u e + u p \end{pmatrix}. \tag{2}$$

The flows $\mathbf{G}(\mathbf{U})$ and $\mathbf{H}(\mathbf{U})$ also will be written by analogy (2).

We will use equation of state for ideal gas for equations system closure

$$p = \rho(\gamma-1)\left[e - \tfrac{1}{2}(u^2+v^2+w^2)\right], \tag{3}$$

here γ is the ratio of specific heats and appears as a fluid property, ρ is the density, $\mathbf{v} = \{u, v, w\}$ is the vector of speed and P is the pressure.

2.1. Dimensionless

Let us bring the system of three-dimensional Euler equations to a dimensionless view. For this purpose let us represent each function as $f = f_0 f'$. Here f'—dimensionless value, f_0—some constant dimensional scale factor. Typical values, which take part in the problem, are used as such scale factors. All values are brought to dimensionless ones in the following way:

$$t = t_0 t', \quad x = x_0 x', \quad u = u_0 u', \quad v = v_0 v', \quad w = w_0 w',$$
$$p = p_0 p', \quad \rho = \rho_0 \rho', \quad e = e_0 e'.$$

After carrying out calculations with the help of the introduced scale factors, it is possible to bring the calculated values to the dimensional view.

For getting dependence between dimensional and dimensionless values in large range let us use the dependence between typical sizes and sound velocity [6]. The most common approach is based on the construction of physical time of the problem with the help of the Mach number M, initial radius R of bubble and sound velocity c in the ambient gas $t_0 = R/Mc$. The sound velocity for air when 20 °C is c=334 m/s, density is $\rho = 1.163$ kg/m^3. Then normalising factor is $t_0 = 1.53 \times 10^{-5}$ s = 0.0153 ms.

2.2. Initial and boundary conditions

The calculated area is presented by parallelepiped with sizes S_x=0.4096, $S_y = S_z = 0.1024$ m. Cells sizes are $d_x = d_y = d_z = 0.0001$ m. Bubble radius is R=0.0128 m and its center is in the point with the coordinates x_c=0.1493, $y_c = z_c = 0.0512$ m. At the left and right boundaries of the calculated area, conditions of free fluxion are being set. At the rest boundaries, periodical boundary conditions are implemented.

We will write the quantity values in the environment with index a, in the bubble—with b, behind the front of shock wave—with h. In the initial time moment the area