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**THE EFFECTS OF JOINTS IN TWO BERYLLIUM
HEMISPHERES USED TO FORM AN IGNITION CAPSULE
FOR THE NATIONAL IGNITION FACILITY**

**S.A.Bel'kov, S.V.Bondarenko, L.A.Ilkaeva, G.G.Kochemasov, L.S.Mkhitarian,
O.A.Vinokurov, N.A.Ryabikina**

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INTRODUCTION

2-D numerical results under the program "MIMOZA" were presented in the report for the first stage [1]. These results were obtained from solution of the problems of the shock wave passage through a joint between two flat beryllium plates which is filled with Al. Two problems have been considered with varying joint (gap) width. It was demonstrated, that the intrinsic oscillations, arising in a narrow gap ($h=1 \mu\text{m}$), have an amplitude comparable with the gap width, therefore they must have essentially nonlinear character, resulting in fast mixing with the surrounding matter.

In case with a wide gap ($h=10 \mu\text{m}$) the intrinsic oscillations amplitude was small as compared with the gap width and the oscillations were close to the linear mode. Consequently while discussing the results of the first stage it was declared reasonable to consider two problems during the second stage:

a) for a narrow gap in calculation of two shock waves passage through the ideal gap - to take into account the possibility of mixing progression;

b) for wide gap - to study the evolution of Kelvin-Helmholtz instability when passing of one shock wave through the gap, which width is modulated from the law:

$$h = h_0 + A \cos\left(\frac{2\pi x}{\Lambda}\right), \quad (1)$$

where perturbation amplitude $A=0.1 \mu\text{m}$ with $\Lambda=10 \mu\text{m}$.

Shock waves are generated when the left boundary of the flat plate is irradiated by X-ray flux and propagate along the axis X .

Radiation temperature T_r for the problem (b) within total time of shock wave passage was constant and was equal to 100 eV, and for the problem (a) at the moment of time from $t_1=4.2 \text{ ns}$ up to $t_2=4.3 \text{ ns}$ radiation temperature linearly increases up to the value $T_r=160 \text{ eV}$. Thickness of the plate in all calculations was the same - $150 \mu\text{m}$.

In the given report we present the results of simulations of these two problems. In all the figures given below we choose $100 \mu\text{m}$ as the unit of length.

I. METHOD OF CALCULATION OF FLOWS WITH MIXING APPLIED IN "MIMOZA" CODE

Although "MIMOZA" code makes it possible to calculate flows with considerable deformations by means of Lagrangian-Eulerian algorithm, such method would have demand practically unattainable reducing of spatial mesh. That is why we used somewhat different approach that we applied in calculations in [1].

Let us set out the system of differential equations for calculations of the multigroup spectral diffusion problems.

The system of 2-D differential gasdynamics equations

$$\frac{d\mathbf{u}}{dt} = -\frac{1}{\rho} \text{grad}(P + Q); \quad \frac{d\mathbf{z}}{dt} = \mathbf{u}; \quad \frac{d\rho}{dt} = -\rho \cdot \text{div } \mathbf{u}; \quad (2)$$

$$\frac{dE_f}{dt} = -p_f \frac{d\left(\frac{1}{\rho}\right)}{dt}; \quad \frac{dE_e}{dt} = -p_e \frac{d\left(\frac{1}{\rho}\right)}{dt}; \quad \frac{dE_i}{dt} = -(p_i + Q) \frac{d\left(\frac{1}{\rho}\right)}{dt}; \quad (3)$$

where $\mathbf{z} = (x, y)$, $\mathbf{u} = (u, w)$, $p_f = p(\rho, E_f)$, $p_e = p(\rho, E_e)$, $p_i = p(\rho, E_i)$, $P = (p_f + p_e + p_i)$, p_f, E_f - are pressure and energy of radiation, p_e, E_e - are pressure and energy of electrons, p_i, E_i - are pressure and energy of ions.

In integrating of gasdynamics equations (2-3) the Langrangian-Eulerian method combined with method of concentrations have been used. Integrating is performed within two stages. At the Lagrangian stage the calculated grid nodes are considered "frozen into the matter" and move together with it. At the Eulerian stage a new differential grid construction is carried out. All thermodynamic values and velocities are recalculated from the old differential grid to a new one. While constructing a new grid we obtain the nodes coordinates on the basis of coordinates of the old grid nodes, being the nearest "neighbors" of the given unit.

The essence of method of concentrations is contained in the fact that several different matters may be present in one calculation cell. The following values are introduced for these matters individualization: mass concentrations $m_i = M_i/M$, where M - mass of a cell, M_i - i -matter mass in the given cell, specific energy values $e_i = E_i/M_i$, where E_i - i -matter internal energy, volume concentrations $v_i = V_i/V$, where V - volume of a cell, V_i - i -matter volume in the given cell. When calculating flows from the mixed cells, algorithm based on local restoration of contact boundary by of field of concentrations analysis is used. And on the basis of this analysis consequence of matter outflow from the accounting cell. The idea of such algorithm is presented in work [2-3]. The essence of the algorithm may be cited by a simple example. Assume that we have two cells - A and B.

The cell A is mixed and contains two matters - 1 & 2, and the cell B has only matter 1. Matter 1 flows from the cell A into the cell B, and after it exhausts, matter 2 starts to flow in the same direction. Such algorithm permits to considerably limit calculating diffusion.

Calculation of equations of hydrodynamics with concentrations is possible under different assumptions of gasdynamic equation systems closure in the mixed cells. Normally the following assumptions are used:

1. equal compressibility of matters

$$\text{div } \mathbf{u}_i = \text{div } \mathbf{u} ,$$

2. equality of matters' pressures

$$P_i = P ,$$

3. equality of matters' temperatures

$$T_i = T ,$$

When performing calculations of the problems examined the third supposition has been used. Its application seems to be the most justified, because due to the high electron or radiation heat conductivity of the medium, temperatures of individual components of matters must quickly level off. Incidentally the average ion model for calculation of equation of state and transport coefficient has natural generalization for the mixed cells with leveled components' temperature. Pressure in the cell is determined by the temperature, average charge and average atomic weight, the latter is calculated by the following formula:

$$\langle A \rangle = \frac{1}{m_1/\langle A_1 \rangle + m_2/\langle A_2 \rangle},$$

where m_1 and m_2 - mass concentrations of matters 1 and 2, $\langle A_1 \rangle$ and $\langle A_2 \rangle$ - their average atomic weights.

Recalculation of the values is performed applying the ideas of algorithm FCT [4]. It is based on the scheme of splitting in directions and on utilization of 1-D high precision algorithm. Elevation of accuracy is achieved by putting into each cell distribution of the recalculated values, which differs from the constant one.

This distribution is put in so, that to provide recalculation of the convective terms with the second order of accuracy in smooth solutions.

Let us set y_1, y_2, y_3 are some value in three consequent cells accordingly. In this case this value distribution in the average cell is selected as follows:

1. if $y_1 < y_2 < y_3$; then $\Delta y = \min(y_3 - y_2, y_2 - y_1)$;

$$y(x) = y_2 - 0.5 \cdot \Delta y \text{ for } x < 0.5 \cdot (x_2 + x_3),$$

$$y(x) = y_2 + 0.5 \cdot \Delta y \text{ for } x \geq 0.5 \cdot (x_2 + x_3)$$

2. if $y_3 < y_2 < y_1$; then $\Delta y = \min(y_1 - y_2, y_2 - y_3)$;

$$y(x) = y_2 + 0.5 \cdot \Delta y \text{ for } x < 0.5 \cdot (x_2 + x_3),$$

$$y(x) = y_2 - 0.5 \cdot \Delta y \text{ for } x \geq 0.5 \cdot (x_2 + x_3)$$

In all other cases value distribution in a cell is considered as constant. Onwards common algorithm of donor cell is used.

In recalculation of thermodynamic values and velocity the laws of conservation of mass, of internal and kinetic energy are fulfilled.

After the gasdynamic stage the following equation are being consequently solved:
equation of spectral radiation transport

$$\frac{\partial U_v}{\partial t} + \text{div} \frac{c}{3\chi_v^{abs}} \text{grad} U_v = j_v - c\chi_v^{abs} U_v,$$

$$\rho \frac{dE_e}{dt} = c \sum_v (\chi_v^{abs} U_v - j_v/c);$$

equation of energy transport by electrons and ions

$$\frac{\partial E_e}{\partial t} = -\frac{1}{\rho} \text{div}(\chi_e \cdot \text{grad} T_e), \quad \frac{\partial E_i}{\partial t} = -\frac{1}{\rho} \text{div}(\chi_i \cdot \text{grad} T_i);$$

equation of energy exchange between ions and electrons

$$\frac{dE_e}{dt} = A(T_i - T_e), \quad \frac{dE_i}{dt} = -A(T_i - T_e).$$

Transport coefficients χ_v, χ_e, χ_i and coefficients of electron-ion relaxation A are being calculated when solving equations of kinetics of ionization in average ion approximation for the mixture of components in the cell.

II. NARROW GAP

As it was shown in the report for the first stage [1], quasi-stationary skewed shock wave moves along the gap. After the shock wave front the flow takes a turn at angle χ , determined by the ratio between density of matter inside and out of the gap. This turn of the flow results in the gap oscillations of its own with large amplitude. Besides, at the Be-Al interface when the flow turns, a tangential rupture of velocity occurs connected with the fact, that the shock wave inclination angles in beryllium and aluminum differ (refer to Fig. 4 and equation (6) from [1]). Actually velocity of matter in the frame, connected with the shock wave front, is

$$u = D \sqrt{1 - \sin^2 \varphi \frac{4\gamma}{(\gamma + 1)^2}}, \quad (4)$$

where φ is the angle of the shock wave front inclination.

Since in the case with the narrow gap $\sin(\varphi_{\text{Be}}) < \sin(\varphi_{\text{Al}})$, velocity of the matter flow in beryllium is higher than that in aluminum, therefore twisted flows arising with the development of Kelvin-Helmholtz instability at the interface should rotate counterclockwise. Temporal evolution of the gap shape in 2-D calculation under "MIMOZA" code is shown in Fig. 1. It is clear from the Figures that development of instability quickly transfers to non-linear stage, so by the moment $t=2$ ns twisted flow system is formed, which rotate counterclockwise. As time goes on these twisted flows totally destroy the gap into separate fragments, so as the Fig. 1 demonstrates, by the moment of time $t=4.8$ ns, when the second shock wave is being formed, the complete gap is not existing any longer. The second shock wave propagates through almost homogeneous matter.

In Fig. 2 various moments of plasma density distribution in the vicinity of the gap behind the shock waves front are shown. We notice that in comparison with density distribution for the same moments of time in analogous calculation in [1], taking account of mixing essentially levels density in the vicinity of the gap.

The selected calculation method permits to trace the stage of heterogeneous mixing. However the size of the minimal fragments is limited by the sizes of the calculation cells and, accordingly, by the computer memory and speed. We notice that in accordance with the expectations in [1], the gap destruction and the stage of heterogeneous mixing comes practically immediately after the front of the first shock wave.

$t=1.8 \text{ ns}$ $t=2.0 \text{ ns}$ $t=2.2 \text{ ns}$ $t=2.4 \text{ ns}$ $t=2.6 \text{ ns}$

Fig. 1. Distribution of Al concentration (gap shape) on various moments of time in the problem on two shock waves passage through a narrow joint.

a) $t=2.0$ ns b) $t=4.0$ ns

Fig. 2. Plasma density distribution in the region of the shock wave in various moments of time in the narrow gap calculation.

III. SHOCK WAVE PROPAGATION ALONG THE WIDE GAP WITH ITS INITIAL SHAPE DISTURBANCES

In accordance with the agreement we have performed calculation of the shock wave propagation through the gap with the initial width $h=10\text{ }\mu\text{m}$, the boundary between Al and Be therewith was disturbed according to (1). As calculation indicates, perturbations do not progress with the disturbance wavelength $\Lambda=10\text{ }\mu\text{m}$ and its initial amplitude $A=0.1\text{ }\mu\text{m}$ ($Ak\approx 0.063$), and the arising inherent gap oscillation occur in linear mode.

In Fig. 3 temporal evolution of the gap shape in this case is shown. As we can see the gap shape practically duplicates calculation made in the case without disturbances (refer to [1]). Such behavior is connected with the fact that the initial amplitude of the gap boundary disturbances is considerably less than the amplitude of oscillations initiated by the turn of the flow behind the front of the skewed shock wave.

A question arises, whether the character of disturbances evolution will change with the increase of their initial amplitude. In this connection calculation has been made with the five-fold increase of the initial amplitude ($Ak\approx 0.3$). As it is shown in Fig. 4, in this case disturbances during the shock wave passage practically do not grow with time as well. However with $Ak=0.3$ disturbances find themselves in non-linear stage from the very beginning and in the course of time the gap shape starts to be determined by more and more short wave modes. We note that the gap boundary shape resembles the shape of a saw tooth, incidentally the teeth are inclined towards the shock wave front. This is connected with the fact that in the wide gap case $\sin(\varphi_{Be}) < \sin(\varphi_{Al})$, therefore flow velocity in Be is less than that in Al (see equation (2)) and the developing twisted flow should rotate clockwise, what is clearly seen in Fig. 4. We can also observe that after the shock wave passage the disturbance wavelength decreases four-fold in accordance with the expectations $(\gamma+1)/(\gamma-1)\approx 4$, and for $\Lambda_0=10\text{ }\mu\text{m}$ is as much as $\Lambda_1=2.5\text{ }\mu\text{m}$. Along with it the inherent oscillations' wavelength is $\Lambda_1\approx 10\text{--}12\text{ }\mu\text{m}$ (refer to [1]), so the wavelength of the inherent oscillation may contain as much as 4÷5 disturbance wavelengths. It would be of certain interest to clear out whether the evolution of disturbances is affected by close proximity of the disturbance wavelength with the one of inherent oscillations. To clear up it two calculations have been performed with the disturbance wavelength $\Lambda_0=50\text{ }\mu\text{m}$ and the initial amplitudes $A=0.1$ and $0.5\text{ }\mu\text{m}$ ($Ak=0.012$ and 0.06 accordingly). In Fig. 5 and 6 temporal evolutions of the gap shape in these calculations are presented. Here we notice that although the disturbance wavelength after the shock wave passage is close to the inherent oscillations wavelength, no disturbance growth occurs. This is due to the fact that the turn of the flow is equivalent to the force, which phase remaining constant, does not correlate with the phase of the oscillations being excited. Therefore no resonant phenomena occurs. Since the disturbances for the selected values of the amplitude are located in the linear stage, we do not observe their impact on the gap shape, which coincides with the ideal flat gap calculation (refer to [1]).

Fig. 3. Distribution of Al concentration at different moments of time in calculation with the perturbation wavelength $\Lambda_0=10$ μm and amplitude $A=0.1$ μm .

Fig. 4. Distribution of Al concentration at different moments of time in calculation with the perturbation wavelength $\Lambda_0=10$ μm and amplitude $A=0.5$ μm

Fig. 5. Distribution of Al concentration at different moments of time in calculation with the perturbation wavelength $\Lambda_0=50$ μm and amplitude $A=0.1$ μm .

Fig. 6. Distribution of Al concentration at different moments of time in calculation with the perturbation wavelength $\Lambda_0=50$ μm and amplitude $A=0.5$ μm .

CONCLUSION

The following conclusions may be drawn on the basis of research carried out:

1. In the narrow gap case turn of the flow initiates inherent oscillations of the gap, which amplitude is comparable with its initial width. Therefore gap oscillations occur in non-linear mode and progressing Kelvin-Helmholtz instability leads to fast heterogeneous mixing of the gap material with the surrounding matter.
2. In the wide gap case availability of the initial perturbations of its shape does not lead to detectable perturbations growth. For the initial disturbance amplitudes, when $Ak \ll 1$ perturbations do not leave linear regime within all the time of shock wave passage through the gap. Perturbations with $Ak \geq 0.3$ from the very beginning develop in non-linear stage and in the course of time the gap shape is more and more determined by the short wave modes.
3. Research carried out permits to suppose that by special selection of width and material at the joint place of two beryllium plates one may attain that there is no turn of the flow and the shock wave propagation will go on the way it does in homogeneous medium.

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