EVALUATION OF HYDRODYNAMIC INSTABILITIES IN INERTIAL CONFINEMENT FUSION TARGET IN A MAGNETIC FIELD

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Magneto-inertial fusion (MIF) or inertial confinement fusion with magnetized target implosion is considered. Laser-driven MIF allows to compress the preseeded magnetic field to thousands of teslas. Model of high pulse energy laser target interaction is presented. Richtmyer-Meshkov (R-M) instability is investigated for MIF systems. We have shown that there is a possibility to suppress the R-M instability by magnetic field. Modeling the impact of magnetic field on a single plasma jet formed at the ICF laser target compression is performed. It is shown that at the compression and heating of a plasma target by using a rapidly growing external magnetic field and laser radiation the R-M instability can be suppressed.

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STATEMENT OF THE PROBLEM

There is one of the promising ways to create thermonuclear plasma: magnetized target and lasers which are used to heat and compress targets to ultra high parameters [1-6]. In this case, external special areas of fusion targets vaporizes because of high-power laser and disperses into the environment at high speed, which provides reactive pressure and compression of the inner layers of the laser target. Moreover, the expansion of the outer layers of the laser target is accompanied by acceleration contact boundary (between the target and environment), which in accordance with the initial conditions (laminated target) density may rise suddenly. It may be the cause of hydrodynamic instabilities, such as Rayleigh-Taylor instability or Richtmyer-Meshkov instability, in the presence of burn acceleration. They accompanied by turbulent mixing of inert material and fuel, which makes difficult to achieve the optimal parameters of thermonuclear fusion. To study this problem, the following task [7] was formulated: research single-mode and multimode disturbances of a contact boundary (contact surface was disturbed by sinusoidal waviness), which is a thin film that separates the two gases (e.g. krypton-xenon with different densities). It was founded that "mushroom" structures [7] were observed in the late nonlinear stage of Richtmyer-Meshkov instability. These structures can be interpreted as a system of pulsed plasma jets with a toroidal vortex behind the leading part of each pulse jet. Thus, suppression of hydrodynamic Richtmyer-Meshkov instability is a very actual topic for laser confinement fusion.

Recall that the Richtmyer-Meshkov instability occurs between two contacting continuous agents with different densities, when the interface is accelerating, e.g. the shock wave. Development of the instability begins from the small-amplitude perturbation, and can pass through four stages – linear ("regular" mode) and a non-linear, transitional and turbulent mixing ("irregular" mode, which is accompanied by a mix of substances). In the "regular mode" of the instability development, which matches to the linear stage, the perturbation growth rate is proportional to the wave number $k = \frac{2\pi}{\lambda}$ [8, 9]. Then the "irregular" regime starts, it is characterized by the fact that the shape of the contact surface disturbance is different from the sinusoidal and consists of a pulse jets "heavy" gas (plasma), which are injected into space flooded with light ($\rho_1 > \rho_2$) gas (plasma). It was observed that, this system of jets at a later time takes the "mushroom" structures form and matches to the conversion (by mixing jets) to the stage of turbulent mixing zone’s formation.

The question arises is it possible to suppress the Richtmyer-Meshkov instability if $\rho_1 > \rho_2$ (heavy gas is blown into the light gas) by some external influence, e.g. by applying an external magnetic field. In order to answer this question, we offer the model of the "irregular" regime of Richtmyer-Meshkov instability as a separate stream (pulse capillary discharge jet) or system of pulsed plasma jet of matter ($\rho_1 > \rho_2$) with density ρ_1. This stream flows in flooded space with density ρ_2 under the influence of the external magnetic field.

A single pulse jet is formed by capillary discharge, which can create a discharge system. Structurally, it is an interelectrode dielectric insert, made in the form of a cylinder with an axial slot opening, which is a channel of capillary discharge, electrodes and case. The electrodes are in the form of flat steel plates, one of which closed a capillary discharge channel from the one side. Initial evaporation and subsequent breakdown of the plasma substance was implemented with an electric explosion inside the capillary metal conductors. Aluminum, copper or lead was used as the plasma-forming substances.

Some results of numerical study of the influence of external magnetic field on plasmodynamic processes occurring in the jets, flowing in stationary medium (air at atmospheric pressure), are presented below. Dynamic parameters of the flowing out capillary discharge channel in flooded area were calculated. A new approximate mathematical model assumes that the electrical energy stored in a capacitor, converted into thermal energy of plasma, which flows out with the sound velocity through the capillary cut.

RESULTS OF CALCULATIONS

Specific calculations were made for a single erosion jet (the plasma-forming material is aluminum) flowing out of the channel of the capillary discharge with an evaporating wall (CDEW) into the cylindrical chamber filled with air at the initial time under normal conditions. This cylindrical chamber faces the flat side of the other slice of capillary discharge is associated with entry into the computational domain through which the erosion plasma flows in the flooded space filled with air.

The value of the total energy stored in the capacitor for a single version of the CDEW is 2.7 kJ, the channel diameter is 10 mm, the channel length of the CDEW is 50 mm, the distance between individual CDEWs is 60 mm. The timing of the peak discharge current is $t_{\max} = 25$ mks. The radial distance between capillary channels varies between 2 and 10 cm, the focus point (with coordinates $Z = \text{var}, r = 0$) on the line of capillary jet torches varies between 3 and 5 cm. Focus point's coordinate Z is measured from the plane where capillaries' slices are situated.

Time dependence $t\left[mks\right]$ on the longitudinal velocity $\text{v}\left[m/s\right]$ (left) and temperature $T\left[\text{K}\right]$ (right) obtained for a particular version of CDEW (cross section of the capillary), based on an approximate mathematical model describing plasmodynamic processes inside the channel of a capillary discharge is presented in Fig. 1.

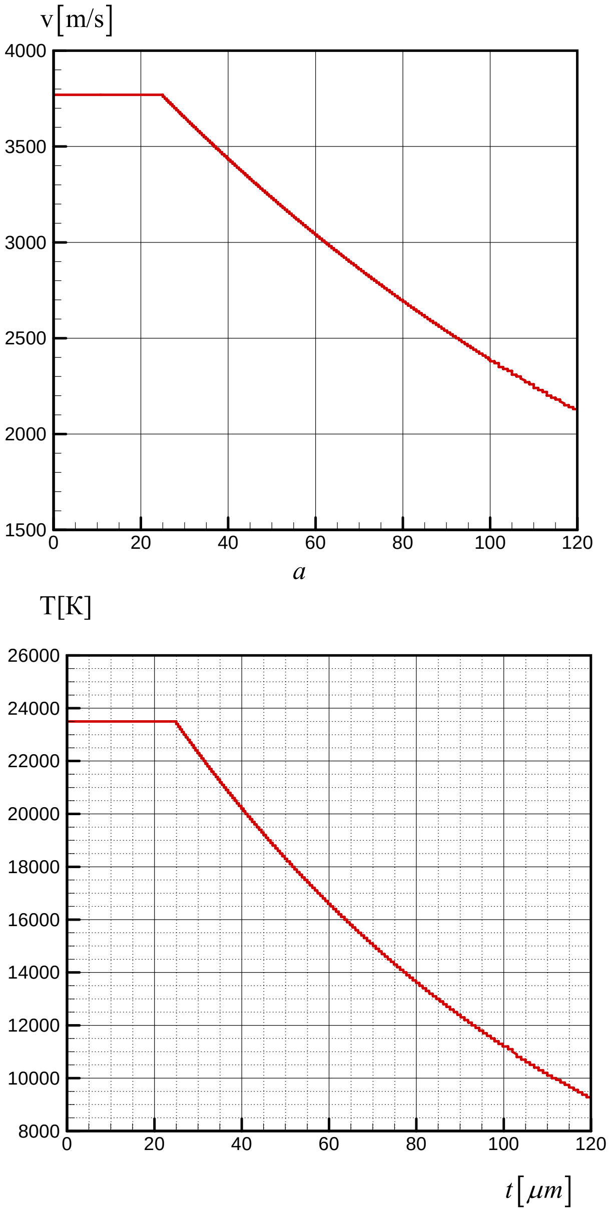
Graphic dependences shown in Fig. 1, and set out in the functional form, are used on the CDEW cross section as boundary conditions in the mathematical modeling of the outflowing plasma jet. The computational domain was presented as a rectangle during the two-dimensional calculations in the coordinate system (r, z).

In the case of a rectangular computational domain there're CDEW off channel cross section in the lower part of the picture on a flat surface. Through that flat surface, erosion flux of plasma-forming substances, which occur within the channel CDEW (*Al* in the calculation), flows into the estimated area.

Top of the rectangular computational domain is also limited by the flat surface (straight line in Fig. 1), where not disturbing "soft" conditions are set on the leaving computational domain flux: $\frac{\partial^2 \vec{f}}{\partial x_n^2} = 0,$ where $\vec{f} = \left\{\rho, u, \text{v}, e\right\}$ and x_n is coordinate normal to the boundary surface.

In the second variant computational domain in the coordinate system (r, z) is a cylindrical chamber which is in the upper part turns into the Laval nozzle. The erosion plasma of capillary's material flows in air-filled space through the outlet section of the nozzle. In the bottom of flat part of the cylindrical chamber there are output CDEW channels. At the top of the flat part of the calculated area variables have "soft" boundary conditions.

Range of integration is limited by the axis of symmetry on the right side. This axis is given by the appropriate symmetry conditions of the plasma capillary discharge.



a

b

Fig. 1. The dependence of the velocity $\text{v}\left[\text{m/s}\right]$ *(a) and temperature T [K] (b) of outflowing plasma on the cut for a particular version of the CDEW on time*

Figs. 2 - 4 show two-dimensional spatial distributions of temperature, which let us to check influence of external magnetic field on the structural elements of a single jet of CDEW.

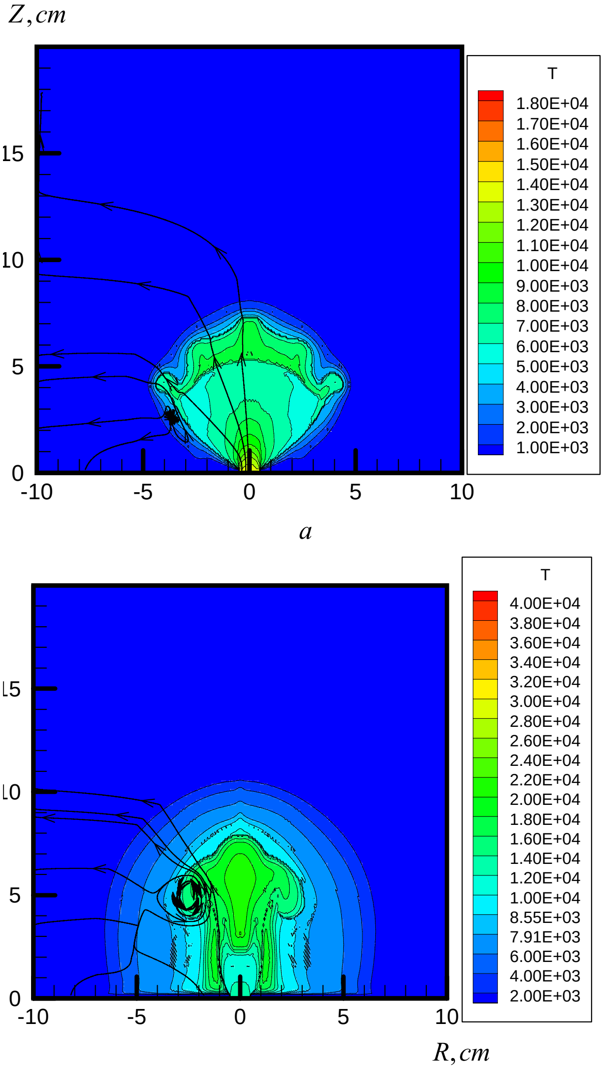
Fig. 2,a shows a flow structure of a single CDEW jet (without external magnetic field) [10, 11], consisting of:

- a group of hanging shock waves;
- the Mach disk, crossed the CDEW axis of symmetry.

The feature of CDEW jet structure is plasma flow in the triple point shock wave configuration. A vortex ring (toroidal vortex) is formed over the central Mach disk (in later times). This track is caused by the fact that dynamic pressure of the stream, which underwent two-stage compression, is much greater dynamic pressure at the central jump [11 - 15].

Figs. 2 and 3 show the temperature distributions in the CDEW torch with external magnetic field on the jet.

Effect of the magnetic field B affects the high temperature (close to the axis) portion of the plasma jet of a single CDEW and wake vortex (toroidal vortex) in the area of triple configuration.



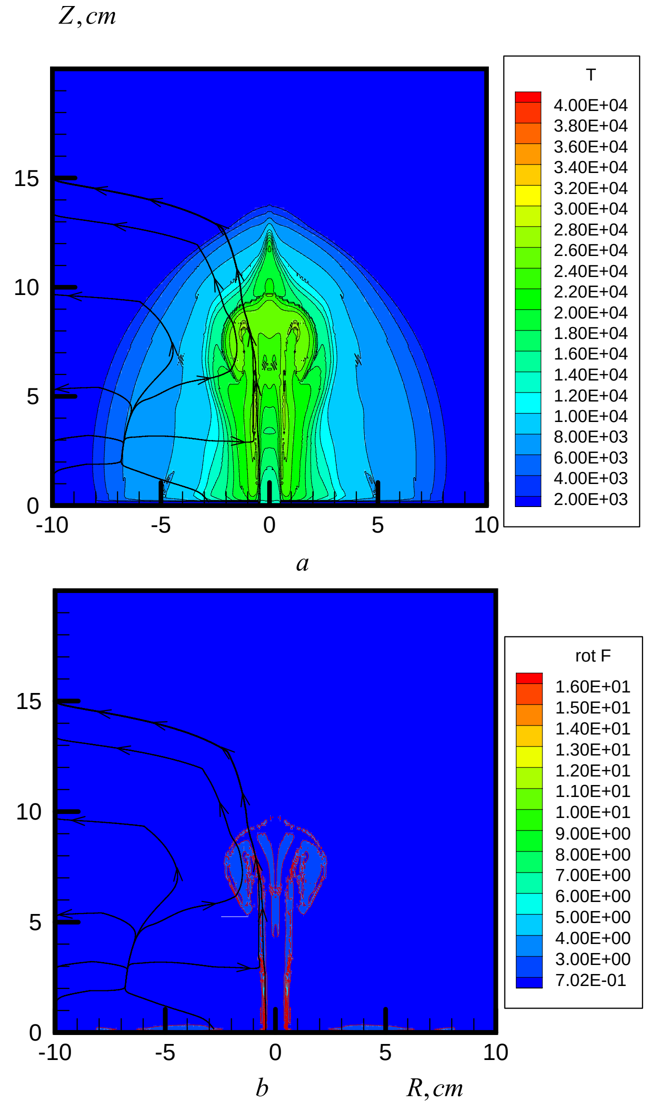
a

b

Fig. 2. The spatial distribution of temperature T [K] in a pulsed plasma jet: (a) without external magnetic field at time t=49.3 μs, (b) in the presence of an external magnetic field B=1.58 T at time t=46.6 μs, and (c) B=2.5 T at t=46.9 μs

The toroidal vortex does not occur, and the longitudinal dimension of the jet CDEW and the maximum temperature T [K] is approximately twice bigger than the size of the jet and the temperature without external magnetic field (see Fig. 2,a) accordingly to the spatial temperature distribution T [K] and the value of the magnetic pressure P_{mag} = 25 [bar], as it follows from Fig. 3,a.

While the distribution (see Fig. 3,b) of vorticity function $\left|rot\left(\vec{V}\right)\right|$ shown that all necessary conditions were created on the border of jet and environment for the occurrence of vortex. The longitudinal size of the CDEW jet and the maximum temperature T [K] is about twice time lower than the size of the jet and the temperature without external magnetic field (see Fig. 2,a).



a

b

Fig. 3. The spatial distribution of temperature T [K] (a) and vorticity function $rot\left(\vec{V}\right)$ (b) in the plasma jet with the external magnetic field B=2.5 T at t=46.9 μs

It is known [11] that characteristic modes of the jet expiry in a gaseous medium are usually described by the off-nominal degree $n = P_a/P_\infty$ (P_a is the pressure on the CDEW cross section, P_∞ is the pressure in the flooded area). The jet is overexpanded for $n < 1$, and underexpanded for $n < 1$. This complex structure of the jet flow in the flooded area is associated with the appearance of the characteristic longitudinal $Z/r_a \approx M_a\sqrt{\gamma_a n}$ and transverse $R/r_a \approx \sqrt{n/(\gamma_a - 1)}$ spatial scales.

When an external magnetic field B = 2,5 T or P_{mag} = 25 bar impact on the CDEW plasma jet the off-nominal degree is $n = P_a/\left(P_\infty + P_{mag}\right) \approx 5,4$ which had to be accompanied with a change in the longitudinal Z/r_a and transverse R/r_a dimensions of the CDEW jet about 5 times.

But, as seen in Fig. 3,a the magnetic pressure P_{mag} has no significant effect on hanging shock waves, after which gas is not very hot ($T \approx$ (3…5) kK). However, in the peripheral zone (see Fig. 2,b), which is adjacent to the axis of the CDEW (T > 10 kK) a reverse flow of plasma occurs (approximately equal to the radial velocity $u(r,z,t)\approx -1{,}3\frac{km}{s}$). This flow is directed towards the axis of the capillary discharge. At the same time the gas-dynamic pressure gradient $\nabla P > 0$ is in the opposite direction, i.e. from the axis of the CDEW torch.

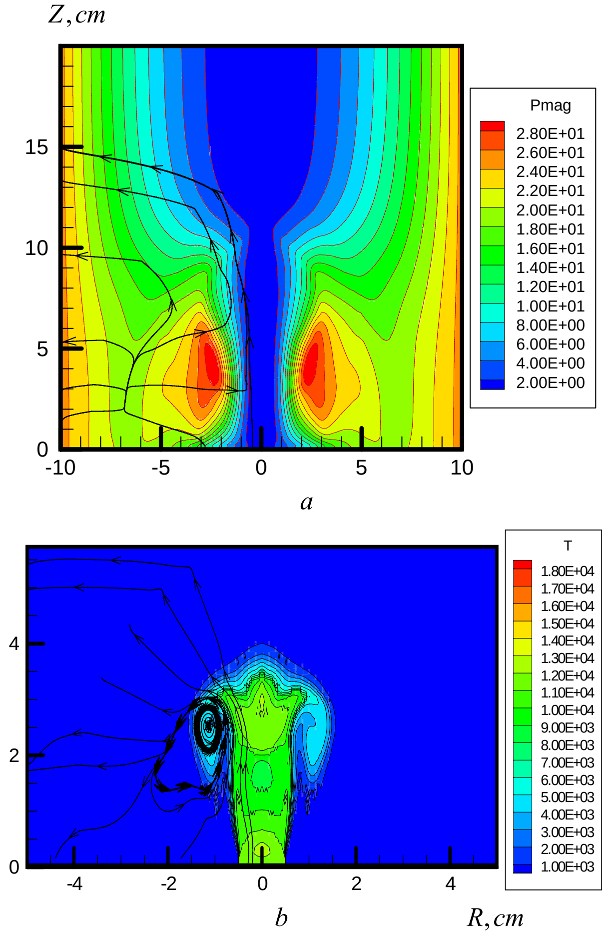


Fig. 4. The spatial distribution of magnetic pressure Pmag [atm] in the magnetic field at t=46.9 µs (a) and temperature T [K] without magnetic field at time t=62.9 µs for pressure in the flooded area $P_\infty = 25$ *atm (b)*

The magnetic pressure has the most noticeable effect (see Fig. 4,a) on the heated part of the axial CDEW jet (T > 20 kK), which is limited by the size of the radial coordinate $R \le 1$ cm. In this spatial area the Mach number is close to unity ($M \approx 1$), and gas-dynamic pressure is $P \approx 100$ bar.

In order to evaluate the level of impact of elevated external gas-dynamic pressure $P_\infty = 25$ bar $\left(n = P_a / P_\infty \approx 5{,}6\right)$ (see Fig. 4,b) shows the temperature distribution in the torch of CDEW without external magnetic field. Note that in this case ($P_\infty = 25$ bar) in the region of mixing of the jet and the surrounding gas environment (in contrast to the presence of an external magnetic field B = 2,5 T) toroidal long-lived the vortex structure is formed, and the maximum temperature in the CDEW jet is $T_{max} \approx 18$ kK, Mach number $M \approx (1\ldots2.4)$, the pressure is $P \approx 10$ bar.

CONCLUSIONS

A mathematical model of pulsed plasma jet flowing into a flooded space is developed. This model is based on equations of radiation plasma dynamics written in arbitrary curvilinear coordinates. Analysis of simple two-dimensional disturbances and composed structures, corresponding to the "irregular" regime of Richtmyer-Meshkov instability is presented. Time dependence of the growth process and disturbances, are obtained. Impact of the external magnetic field on them is investigated. A simplified qualitative model for explanation is offered. Main gas dynamics and radiation parameters of the capillary discharge with an evaporating wall (CDEW) are calculated.

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ОЦЕНКА ГИДРОДИНАМИЧЕСКИХ НЕУСТОЙЧИВОСТЕЙ В МИШЕНИ ИНЕРЦИАЛЬНОГО ТЕРМОЯДЕРНОГО СИНТЕЗА ПРИ НАЛИЧИИ МАГНИТНОГО ПОЛЯ

В.В. Кузенов, С.В. Рыжков

Работа посвящена принципам магнитно-инерциального термоядерного синтеза (МИТС) и лазерно-плазменным методам генерации мегагауссного поля при имплозии замагниченной мишени, что открывает возможности создания новых плазменных источников высокой плотности для применения их в материаловедческих экспериментах и для перспективных направлений энергетики. МИТС с лазерным драйвером позволяет сжать первоначальное магнитное поле до нескольких сотен и даже тысяч тесла. Такие плазменные системы могут использоваться для диагностики и испытаний различных материалов. Неустойчивость Рихтмайера-Мешкова (РМН) исследована для условий МИТС в импульсных системах с инерциальным удержанием частиц. Представлена модель взаимодействия лазера высокой энергии импульса с плазменной мишенью, находящейся в затравочном магнитном поле. Проведено моделирование воздействия магнитного поля на отдельную плазменную струю, образующуюся при компрессии мишени лазерным лучом. Показано, что при сжатии и нагреве плазмы с помощью быстронарастающего внешнего магнитного поля и лазерного излучения возможно подавление РМН.

ОЦІНКА ГІДРОДИНАМІЧНИХ НЕСТІЙКОСТЕЙ В МІШЕНІ ІНЕРЦІАЛЬНОГО ТЕРМОЯДЕРНОГО СИНТЕЗУ ЗА НАЯВНІСТЮ МАГНІТНОГО ПОЛЯ

В.В. Кузенов, С.В. Рижков

Робота присвячена принципам магнітно-інерціального термоядерного синтезу (МІТС) і лазерно-плазмовим методам генерації мегагауссного поля при імплозії замагніченої мішені, що відкриває можливості створення нових плазмових джерел високої щільності для застосування їх в матеріалознавчих експериментах і для перспективних напрямків енергетики. МІТС з лазерним драйвером дозволяє стиснути початкове магнітне поле до декількох сотень і навіть тисяч тесла. Такі плазмові системи можуть використовуватися для діагностики та випробувань різних матеріалів. Нестійкість Ріхтмайера-Мєшкова (РМН) досліджена для умов МІТС в імпульсних системах з інерціальним утриманням часток. Представлена модель взаємодії лазера високої енергії імпульсу з плазмовою мішенню, що знаходиться у затравочному магнітному полі. Проведено моделювання впливу магнітного поля на окремий плазмовий струмінь, що утворюється при компресії мішені лазерним променем. Показано, що при стисненні і нагріванні плазми за допомогою бистронаростаючого зовнішнього магнітного поля та лазерного випромінювання можливо подавлення РМН.