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Modeling of direct conversion of the uranium fission product kinetic energy to laser radiation energy in an argon–xenon dusty plasma with uranium nanoparticles

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Abstract

The process of direct conversion of the uranium fission product kinetic energy to laser radiation (LR) energy in a moving argon–xenon laser-active gas medium containing uranium nanoparticles has been investigated.

A model and a method have been developed to solve numerically equations for the model of direct uranium fission product kinetic energy conversion to laser radiation energy in such medium. Spatiotemporal evolutions of the uranium nanoparticle concentration distribution have been calculated for different gas flow velocities and uranium nanoparticle sizes.

Kinetic processes in a moving argon–xenon laser-active gas medium containing uranium nanoparticles have been studied.

It is the first time that amplifying properties of a laser-active spatially heterogeneous nuclear-excited moving argon–xenon medium, containing uranium nanoparticles and irradiated by neutrons, have been studied. As shown by the investigation results, the LR intensity amplification may be sevenfold and more in steady-state conditions. Such a high value makes it possible to state that this medium can be used not only in a nuclear-pumped laser but also in the mode of a single-pass nuclear-pumped laser amplifier.

Keywords: Mathematical modeling; Conversion; Nuclear energy; Fission; Uranium; Fragments; Kinetic processes; Laser radiation; Moving plasma; Nanoparticles.

Introduction

There has been 40 years since it was proposed to use finely divided uranium-containing particles dispersed in an active gas medium to convert nuclear energy to optical radiation energy [1]. As compared to traditional techniques for heterogeneous nuclear pumping of active gas media, the use of finely divided uranium-containing particles may lead to the share of energy carried out by fission fragments from condensed phase into the gas medium to increase tenfold and more. This creates opportunities for improving the efficiency of nuclear energy conversion to optical radiation energy.

Dispersal and absorption of laser radiation by an active medium with a content of finely divided uranium-containing particles is a major factor that hampers the generation of laser radiation in this medium.

It has been proposed recently to use laser-active gas media irradiated by neutrons and containing nanoclusters of uranium compounds [2–4].

Initially, it was demonstrated by computational and theoretical studies that it was possible to amplify laser radiation in a nuclear-excited argon–xenon dusty gas plasma [2–4].

It was further shown by mathematical modeling methods that during generation of laser radiation (LR) in an argon–xenon gas medium irradiated by neutrons and containing uranium nanoparticles the conversion of the uranium fission fragment kinetic energy to LR energy was an order of magnitude

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as efficient as the conversion of this energy during heterogeneous pumping [7,8]. This makes it possible to expect that a method and devices will be developed with a high efficiency of direct conversion of the fission fragment kinetic energy to the energy of coherent optical radiation.

In [7,8] however, only an immovable homogeneous dusty medium was considered. To prevent uranium nanoparticles from depositing in gas, it appears to be reasonable to blow down this medium. Apart from that, a dusty medium may start to move in the process of irradiation when the heating of gas by fission fragments is non-uniform.

Hence, this dictates the need for the conversion of uranium fission fragment kinetic energy to be studied with the active medium movement taken into account.

This paper deals with mathematical modeling of direct conversion of uranium fission fragment kinetic energy to the energy of laser radiation in a moving neutron-irradiated argon–xenon dusty plasma containing uranium nanoparticles.

The purpose of the study is to determine the effects of the active medium movement and the spatial non-uniformity on the LR amplification process in a laser-active element (LAEL).

Model of the spatiotemporal evolution of the uranium nanoparticle concentration in a dusty LAEL

We shall consider the steady-state movement of a mixture of inert argon and xenon gases in an LAEL in the form of a vertical cylindrical surface. With a steady-state movement of gas with subsonic velocities, dusty nanoparticles of uranium (U) are injected into the LAEL at the initial time $t = 0$. And the relation of the uranium dust mass to the gas mass is small. Therefore, no heavy excitations are caused by the dust during movement, so a Navier–Stokes equation is used to describe the axially symmetrical movement of the gas containing uranium nanoparticles [9]. It may be considered that the gas pressure in the LAEL is approximately constant. We shall use coordinate- and time-dependent functions for modeling.

The feed rate of the gas with a content of uranium nanoparticles is distributed in accordance with a parabolic law [9]. The variation in the concentration of uranium dust in the moving gas may be described by a parabolic equation, taking into account both the diffusion of dust particles and the forces acting on the particles in the gas flow:

$$\partial n/\partial t = D\Delta n - \mathrm{div}(\boldsymbol{j}) \tag{1}$$

where n is the concentration of particles; D is the diffusion coefficient; Δ is the Laplace operator; and $\boldsymbol{j}$ is the density of the dust particle flow equal to

$$\boldsymbol{j} = v_p(r)n, \tag{2}$$

containing $v_p(r)$, the dust particle movement velocity, which may differ from the argon–xenon gas medium movement velocity.

We shall determine the diffusion coefficient D using the approximation proposed in [10]:

$$D = kT(1 + 3.12\ Kn)/\left(6\pi r_p \eta\right), \tag{3}$$

where k is the Boltzmann constant; T is the temperature; Kn is the Knudsen number; r_p is the radius of uranium nanoparticle; and η is the dynamic gas viscosity.

Let the argon–xenon gas mixture move vertically upward, then two forces act on the dust particles in the LAEL. These are downward directed gravity (F_g) and Stokes force (F_d) directed oppositely to the gravity in the direction of the flow velocity. These forces are respectively equal to

$$F_g = m_p g, \tag{4}$$

$$F_d = 6\pi \mathrm{r}_p \eta (v(r) - v_p(r)), \tag{5}$$

where m_p is the particle mass; $v(r)$ is the gas flow velocity; and $v_p(r)$ is the particle velocity.

Equalities (4) and (5) can be used to find the average velocity of the directed steady-state particle movement in the flow depending on the distance from the cylinder axis to the cylinder's inner wall:

$$m_p g = 6\pi r_p \eta \left(v(r) - v_p(r)\right), \tag{6}$$

$$v_p(r) = v(r) - m_p g/\left(6\pi r_p \eta\right). \tag{7}$$

We shall assume further that the velocity v_p becomes steady-state rather fast.

By expressing the particle mass in terms of the particle radius and density, we shall get

$$v_p(r) = v(r) - \left(2\rho_p r_p^2 g\right)/(9\eta), \tag{8}$$

where ρ_p is the particle density.

The velocity at which the gas is fed into the LAEL is non-uniform relative to the tube cross-section. The velocity was described using parabolic distribution [9] of the form

$$v(r) = v_{max}\left(R^2 - r^2\right)/R^2, \tag{9}$$

where $v(r)$ is the current velocity in the radius r; r is the current radius; R is the inner radius of the tube; and $v_{\max}$ is the maximum velocity of the gas (on the axis).

Taking into account equations (2) и (9), we shall transform Eq. (1) to give it the final form

$$\frac{\partial n}{\partial t} = D\left(\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial}{\partial r} n + \frac{\partial^2}{\partial z^2} n\right) - v_{max}\left(1 - \frac{r^2}{R^2}\right)\frac{\partial}{\partial z} n, \tag{10}$$

where z, r are cylindrical (axial and radial) coordinates.

At the initial time, the concentration of dust particles in the LAEL is equal to zero, and dust particles of the preset concentration are fed into it. The process is symmetrical to the LAEL axis. And at the boundary where $r = R$, $N_0 = 0$. The particles stick on the walls. The exit from the LAEL is unobstructed.