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Coupled heat transfer in the cavity of constant volume with pulse-periodical energy supply

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The possibilities of organizing a repetitively pulsed process with given frequency characteristics in a cavity of constant volume with an external energy supply to the working gas mixture are considered. Modelling of gas-dynamic and thermal processes is carried out using the numerical solution of the conjugate heat transfer problem. The gas medium is described on the basis of a viscous compressible gas model. To find the temperature field in the walls of the structure, the equation of non-stationary heat conduction is solved. The conjugation of temperature fields in a gas and a solid is carried out using an iterative procedure. In the calculations, the geometrical parameters of the cavity, the density of the energy supply, the initial pressure, and the composition of the working mixture are varied. The results of calculations obtained in the framework of the one-dimensional and two-dimensional formulation of the problem under the action of both a single pulse and a series of pulses are compared. The results obtained demonstrate the possibility of implementing the required frequency characteristics of the process for given geometric and energy parameters.

Keywords: pulse-periodical energy process, gas laser, coupled heat transfer, numerical simulation, energy supply, pulse.

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Introduction

The study of coupled heat transfer in cavities filled with a medium with heterogeneous parameters is of interest in the development of cooling systems for gas lasers [1]. To ensure the constant composition and pressure of the working gas, the laser is provided with a gas supply system, which plays an important role in the radiation generation mechanism.

In a gas-discharge technological laser, the active element is a chamber filled with a working gas mixture. After the energy supply an excess amount of heat remains in the medium, which leads to increasing of the temperature and pressure of the gas mixture, as well as a change in the physical properties of the active medium [2,3]. Before initiating the next pulse, it is necessary to remove heat and to bring the medium to its initial thermodynamic state. In gas lasers there are two different ways of cooling the working mixture: diffusion and convection. Diffusion cooling of the active medium is provided by heat removal through the cooled walls of the discharge chamber. Convective cooling is carried out by rapid pumping the laser mixture through the discharge chamber. The generation of radiation with stable parameters is achieved through the use of a closed pumping cycle and a regeneration system for the spent laser mixture. The task of the analysis is to determine such system parameters that provide repetitively pulsed operation with specified frequency and energy characteristics.

Various issues related to the implementation of mathematical models of coupled heat transfer in closed cavities are discussed in paper [4]. The coupled problem of heat transfer in a cylindrical finned tube is solved in [5]. The results obtained make it possible to estimate the heating of the liquid along the length of the channel, as well as the temperature difference on the pipe walls. The coupled heat transfer during the motion of a viscous incompressible fluid in an open cavity, taking into account the cooling of the external circuit, is simulated in [6]. A two-dimensional description of the convective stationary heat transfer of a high-temperature cylindrical surface cooled by a liquid flow is considered in [7]. Coupled heat transfer in cavities formed by movable and fixed walls is simulated in [8]. Issues related to the numerical simulation of coupled heat transfer in closed regions with local energy release in the flow are discussed in [9–13].

In this paper we consider the possibility of implementing repetitively-pulsed processes in a region of constant volume filled with a gas mixture. The solution of the problem in a one-dimensional formulation gives a preliminary estimate of the temperature level when energy is supplied to the active mixture, and provides initial data for solving the problem of the state change of the gas mixture during the development in it of gas-dynamic processes, heat transfer processes and processes of heat exchange with the structure. For a more accurate assessment of the temperature level in the working cavity, a two-dimensional model is used. Based on the results analysis of numerical simulation in cavities of various geometric shapes, a conclusion is made about the possibility of organizing a repetitively-pulsed process with given frequency characteristics.

1. Mathematical model

The cavity contains a working mixture of carbon dioxide and helium. The total pressure of the mixture and the partial pressures of its components vary. A laser pulse is introduced into the cavity, for the pulse the dependence of the intensity on time is specified. In the calculations, a trapezoidal pulse with an effective duration $2\,\mu$s is used.

The possibility of realizing a repetitively-pulsed process in the region of constant volume (there is no exchange of gas with the environment) is considered. The pumping pulse passes through the cavity, is reflected from the mirror, and returns to its input window. The gas mixture is cooled due to its heat exchange with the structural elements of the cavity. The gas component state is determined by both the external influence and by the coupled heat exchange with the limiting walls. Since the characteristic time of laser processes is much shorter than the characteristic time of thermal processes, then instantaneous heat supply to the gas mixture is assumed.

For numerical research a set of mathematical models is used. To reproduce the individual elements of the process various simplifications are used, which relate to the dimension of the problem (one-dimensional or two-dimensional), taking into account various factors (heat transfer, convection, radiation). The essential element of the models is taking into account the instability of the process. The gas medium is considered as a mixture of ideal gases. The thermodynamic characteristics and properties of the gas component are functions of the mixture composition and temperature at the considered point. Thermodynamic characteristics, properties of the gas mixture component are presented as polynomes by powers of temperature.

The computational domain consists of a gas cavity and its limiting walls. To find the temperature distribution and gas-dynamic parameters in the gas cavity, the instable problem of gas dynamics is solved, and to find the temperature distribution in the walls limiting the structure, the instable heat-conductivity equation is solved. On the outer boundaries of the computational domain the conditions of free-convective heat exchange and radiative heat exchange with the environment are used, and on the inner boundaries in contact with the gaseous medium the conditions of thermal coupling (equality of heat fluxes and temperatures) are used.

The system of equations of gas dynamics is solved numerically based on the scheme of splitting by physical processes, the elements of which are convective transfer, energy supply and heat exchange with the structure. Convective flows are determined on the basis of the decay scheme of an arbitrary discontinuity. Boundary conditions are set in a characteristic form that takes into account the interaction of pressure waves with the inlet and outlet boundaries of the region. The nonlinear heat-conductivity equation is solved using an implicit difference scheme, which has the second order of approximation in space and the first order in time. The nonlinearities are assigned to the lower time layer, and the radiation conditions are linearized. On this basis, a non-iterative difference scheme is implemented, which is resolved at each step by inverting the matrix of coefficients.

The distributed energy supply is taken into account as a source term in the energy equation. The volume specific energy input at each moment of time is determined from the numerical solution of the Bouguer equation, taking into account the influence of the medium density on the absorption coefficient. For the partial pressure of carbon dioxide of 1 atm and temperature of 300 K, the value of the absorption coefficient is assumed to be $k = 36.67\,\mathrm{m}^{-1}$. The laser pulse intensity is $I_0 = 3.7 \cdot 10^{10}\,\mathrm{W/cm}^2$.

2. One-dimensional model

A flat slit with height h filled with active gaseous medium (Fig. 1) is supplied uniformly over the cross-section with energy with a volume intensity Q and a supply interval Δt. The walls of the slit are assumed to be either copper, or one of them is made of copper, and the another is optical glass. The thickness of the walls limiting the cavity is 20 mm. The heat supply is characterized by the bulk density of energy supply with a given frequency ($f = 10$ Hz). The operating time of the system is assumed to be 2 s, which corresponds to 20 pulses of energy supply.

Calculations are carried out for the gas mixture $0.9\mathrm{He} + 0.1\mathrm{CO}_2$ at pressure $p = 10$ atm. The width of the gas cavity is assumed equal to $h = 5$ mm. The intensity of energy supply is $Q = 1\,\mathrm{J/cm}^3$.

The temperature in the slit at the initial moment takes a high value corresponding to the amount of energy supplied. Further, the gaseous medium cools down due to thermal conductivity. In the case when the time interval between pulses is insufficient for the thermal recovery of the system, the temperature in the cavity by the beginning of the next pulse exceeds the initial value. The dynamics of temperature change at the midpoint of the cavity when the gas in the cavity is heated by a series of successive pulses is shown in Figs. 2 and 3 for various sizes of the gas cavity and

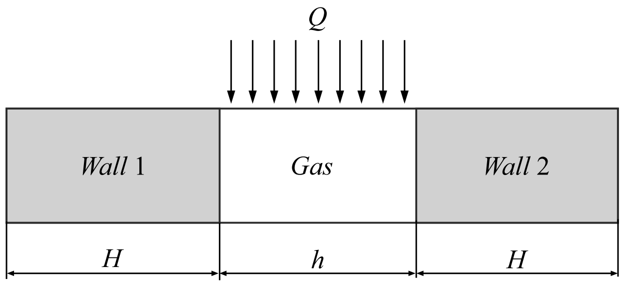

Figure 1. Geometry of the computational domain.

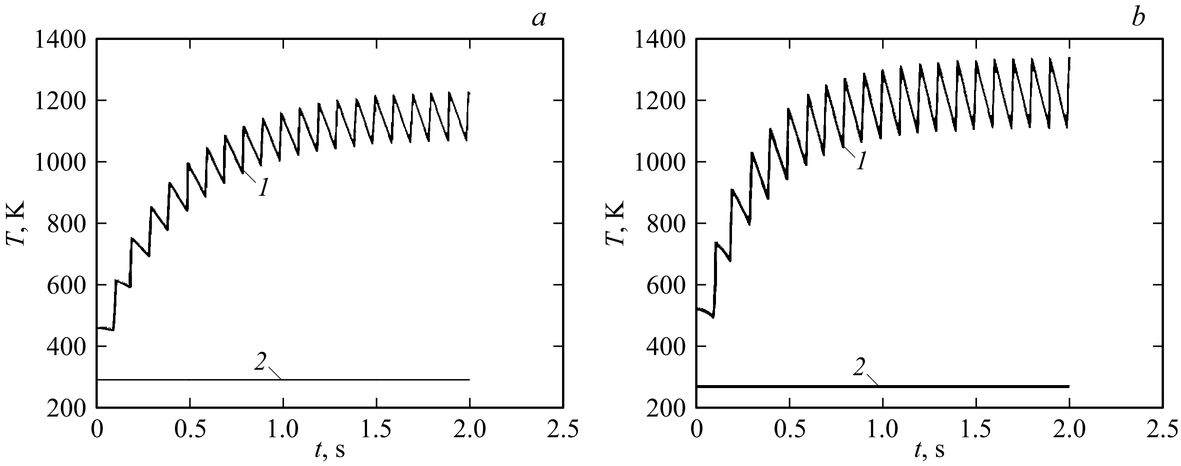

Figure 2. Temperature distribution over time at $h = 5$ mm, $Q = 1\,\mathrm{J/cm^3}$ (a) and $Q = 2\,\mathrm{J/cm^3}$ (b).

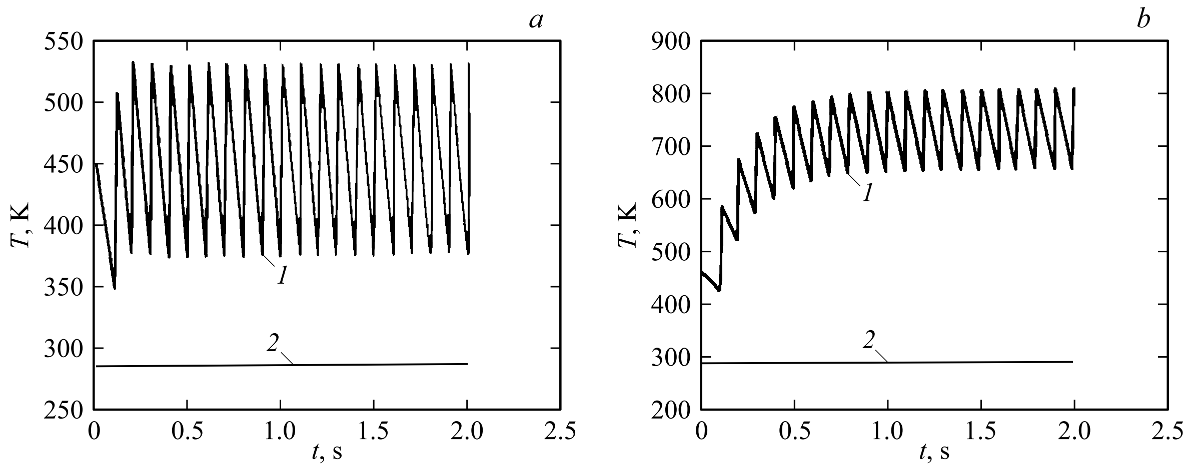

Figure 3. Temperature distribution over time at $h = 3$ mm, $Q = 1\,\mathrm{J/cm^3}$ (a) and $Q = 2\,\mathrm{J/cm^3}$ (b).

intensity of energy supply. Lines *1*correspond to the gas cavity, and lines *2* — to the wall. Under the action of a sufficiently large series of pulses the system enters a certain mode in which it manages to release heat from the next pulse of energy supply. In this case, constant values of the maximum temperature are set after the action of the next pulse, and of the temperature in the middle of the cavity before the action of the next pulse.

The temperature change in the middle of the slit 10 mm wide, for a series of 12 pulses with a frequency of 0.2 Hz is shown in Fig. 4, *a*. Lines *1*correspond to the gas cavity, and lines *2* — to the wall. For a time equal to the period between pulses, the state of the gas is completely restored. Heat is removed to the wall by thermal conductivity. As the pulse frequency increases, the gas does not have time to restore its initial thermodynamic state. Fig. 4, *b* shows the temperature at the midpoint of the gas cavity vs. time for the process with frequency 1 Hz.

The temperature differs from the initial temperature by some value ΔT, which depends on the frequency of the repetitively-pulsed process. Reducing the channel height leads to heat removal increasing. Fig. 5 shows the values of the gas temperature at the cavity midpoint after 10 successive pulses depending on the process frequency. With a small channel height it seems possible to ensure the frequency of the repetitively-pulsed process at a level of 10 Hz. However, the question of the possibility of optical implementation of the process in a channel with such geometrical characteristics is critical.

3. Two-dimensional model

Instable thermal processes are considered with pulsed energy supply to the working area, consisting of copper and quartz surfaces, between which there is working mixture of carbon dioxide and helium $0.9\mathrm{He} + 0.1\mathrm{CO_2}$ (Fig. 6, *a*). Elements designed to remove heat from the gas are immersed in the working space. Gas-dynamic and thermal processes are simulated in the computational domain shown in Fig. 6, *b*. The width of the domain

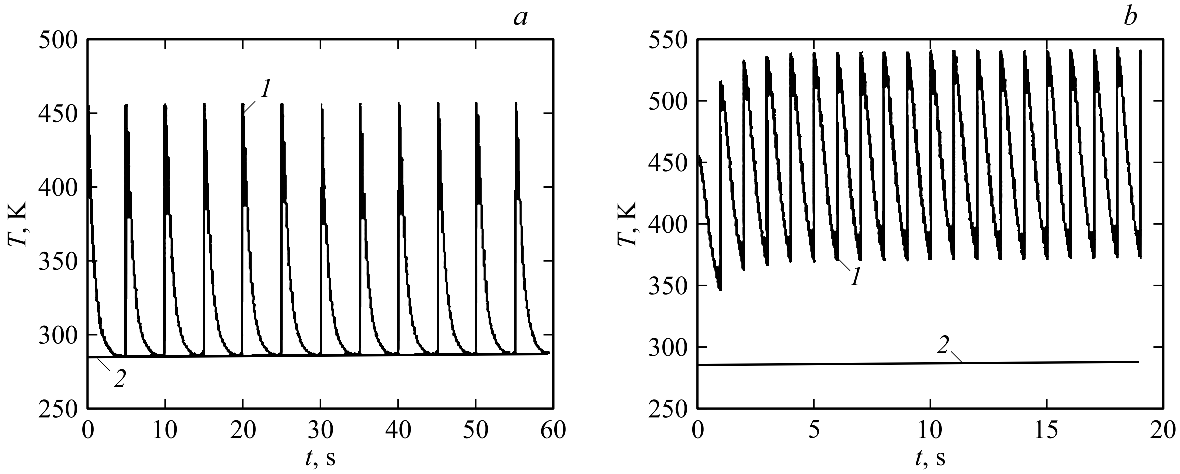

Figure 4. Changes in temperature over time at the midpoint of the gas cavity at $Q = 1\,\mathrm{J/cm^3}$. The interval between pulses is 5 (a) and 1 s (b).

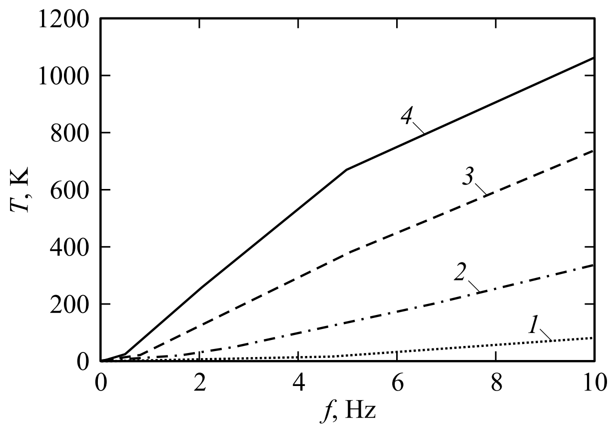

Figure 5. Temperature increment in the cavity after 10 successive pulses depending on the frequency at $h = 3$ (*1*); 5 (*2*); 7.5 (*3*); 10 mm (*4*).

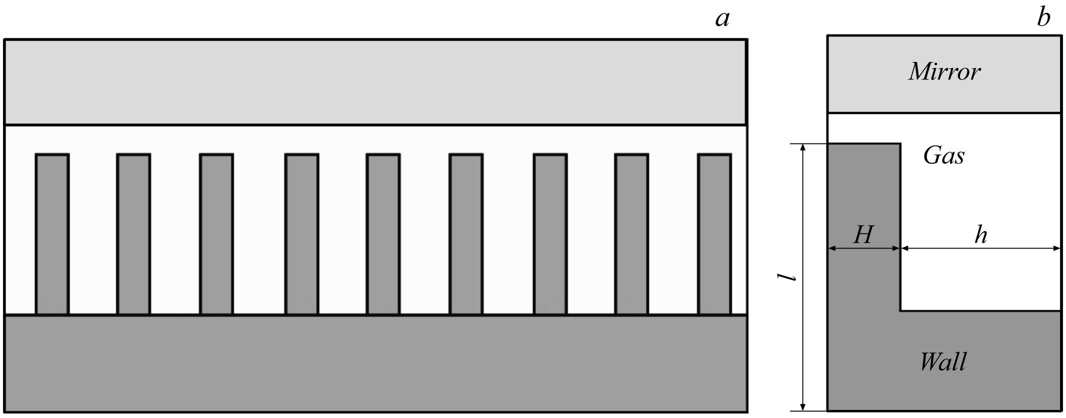

Figure 6. Design of the cavity (a) and computational domain (b).

is assumed to be $h = 3$ mm, the thickness of the fin — $H = 3$ mm, and the height of the domain — $L = 15$ mm. In the calculations a pulse is specified that determines the distribution of the bulk energy input of a trapezoidal shape with an effective duration of 2 μs. The initial temperature of the system is 285 K.

The dynamics of the thermal recovery of the system after the end of the single pulse action is shown in Fig. 7.

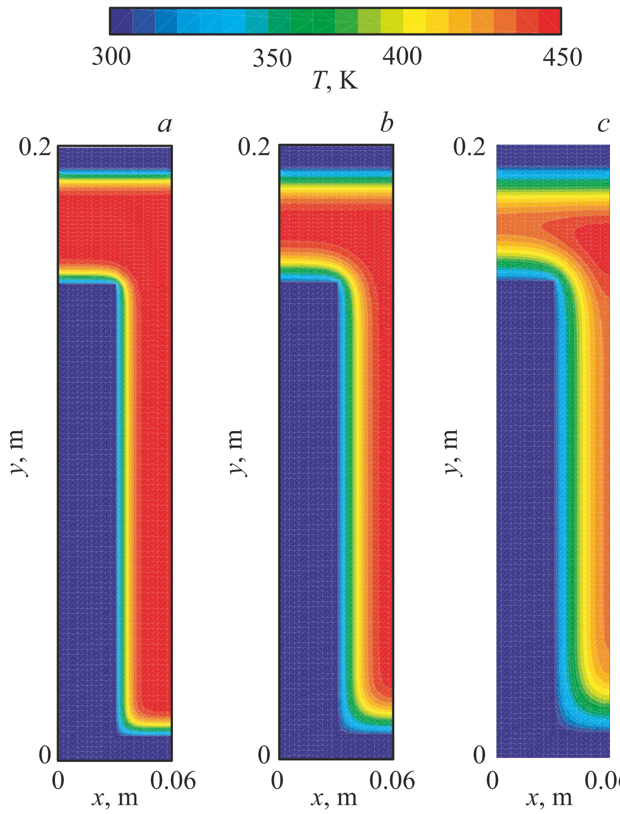

Figure 7. Temperature field after the end of the pulse at times $t = 0.02$ (*a*), 0.06 (*b*), 0.1 s (*c*).

Over time, the temperature field tailing is observed, and the maximum temperature level in the cavity decreases.

The influence of the energy supply on the dynamics of the system is shown in Fig. 8. For the clarity of representation of the results corresponding to models of different geometric dimensions, the moments of pulse arrival are slightly shifted relative to each other. There is a rather accurate agreement between the results of calculations obtained within the framework of the one-dimensional and two-dimensional models. In this case, the maximum difference in the values of the system temperature with repetitively-pulsed supply of energy does not exceed 0.85%.

Conclusion

To organize a repetitively-pulses process a volume with a constant portion of the gas mixture is used. After energy supply thermal and gas-dynamic processes develop in the system. The nature of these processes is determined by the geometric shape of the domain, the design and material of the limiting walls through which heat removal is provided. The spatial non-uniformity of energy supply leads to a significant increasing of gas speeds, which intensifies heat transfer and increases the frequency of the repetitively-pulsed process, and also affects the optical characteristics of the medium.

Mathematical models were developed, and software was created that makes it possible to simulate thermal and gas-dynamic processes in the cavity of repetitively-pulsed system without gas flow. A parametric study of the thermal state of the gas mixture under energy supply by series of pulses in high-pressure active media was carried out to estimate the limiting values of the laser pulses repetition rate. The dynamics of the temperature field is studied depending on the geometric dimensions of the active medium and the design of the laser cavity in the absence of the convective drift of the gas flow. Based on the results the analysis of numerical simulation, the possibility of organizing a repetitively-pulsed process with given frequency characteristics in systems with constant (non-replaceable) active gas component is shown. The calculation results obtained within the framework of the one-dimensional and two-dimensional models are in good agreement with each other.

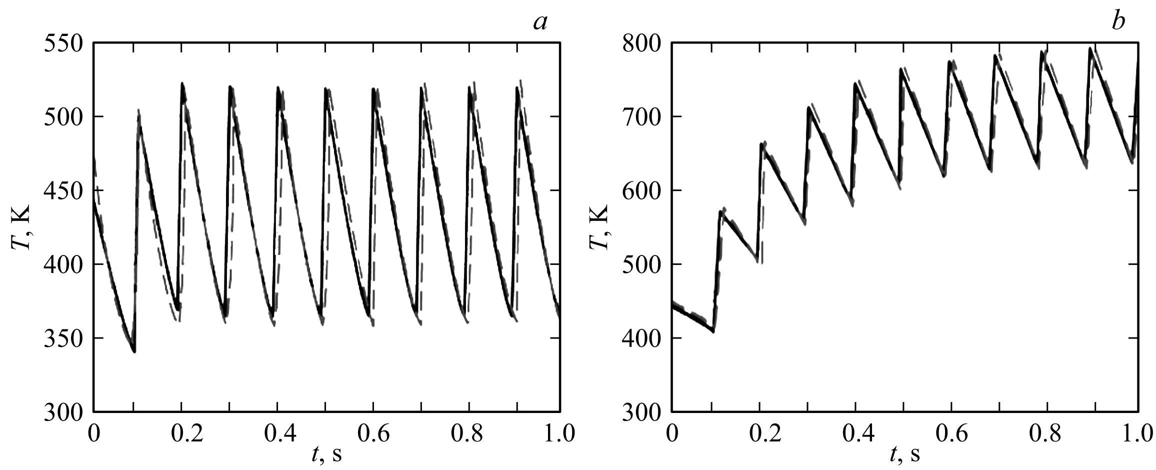

Figure 8. Comparison of temperature distributions obtained on the basis of two-dimensional (dashed lines) and one-dimensional (solid lines) models, at $Q = 1$ (*a*) and 2 J/cm^3 (*b*).

At pulsed energy supply with its non-uniform distribution over the cross-section, the transient gas-dynamic processes occur with significant gradients of parameters. The dimensions of the cavity, which ensure the repetitive-pulsed operation of the system, are determined. Cavities made with heat-removing elements allow for a wide variation in geometric dimensions to optimize laser processes. Schemes with the flow of the working fluid are promising in the sense of thermal recovery of the environment. The technical implementation of such scheme requires further research.

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Conflict of interest

The authors declare that they have no conflict of interest.

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