On the Optimal Choice of Type of Combustion Chamber for the Initiation of Gas Detonation

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Abstract: - A numerical simulation of continuous gas detonation in the combustion chamber based on the Navier-Stokes equations, taking into account turbulence and diffusion of substances, is carried out. A comparative analysis of the efficiency of detonation combustion of fuel depending on the geometric parameters of the chambers is performed. Three possible camera types are considered. Fuel and oxidizer were fed separately into the chambers through nozzles at a certain angle to the chamber surface. The detonation process was largely determined by the intensity of the turbulent mixing of reagents (hydrogen and oxygen). Calculations show that the type of camera with a flat radial geometry is the most optimal to establish a stable detonation regime.

Key-Words: - chamber geometry, modeling, turbulence, compressible flows, heat generation, detonation, mixing.

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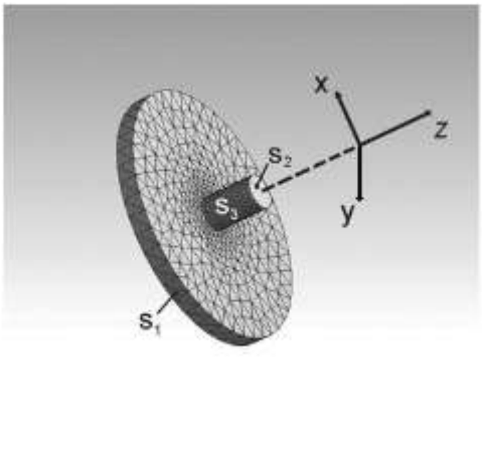
1 Introduction

Recently, active research has been conducted on the creation of an internal combustion engine based on the detonation method of fuel combustion. In this case, much more energy is released during the detonation process with less fuel consumption than during controlled combustion. The theoretical possibility of using detonation in engines is shown in, [1]. Since then, a number of research laboratories have been working to create practical installations and determine the optimal operating modes of such cameras, [2]. In some cases, significant progress has been made, [3]. Recent experimental and theoretical studies, [4], have been performed for various combustion mixtures and installation parameters. The phenomenon of detonation is a complex physicochemical process that is realized at high speeds in the medium. Therefore, the study of the phenomenon and its possible technological applications requires the involvement of detailed mathematical models describing the process of fuel combustion in the chamber. One of the most important aspects of the problem is the geometric shape of the camera. It is usually the volume between two metal cylinders. But a simpler form is a flat, axisymmetric disk.

This work is devoted to a comparative theoretical study of the initial stage of detonation excitation for three different geometric types of chambers. The first type is the volume formed by two metal cylinders (Figure 1a). The second type is an annular chamber inside the cylinder (Figure 1b). The third simplest type is a plane axisymmetric disk (Figure 1c).

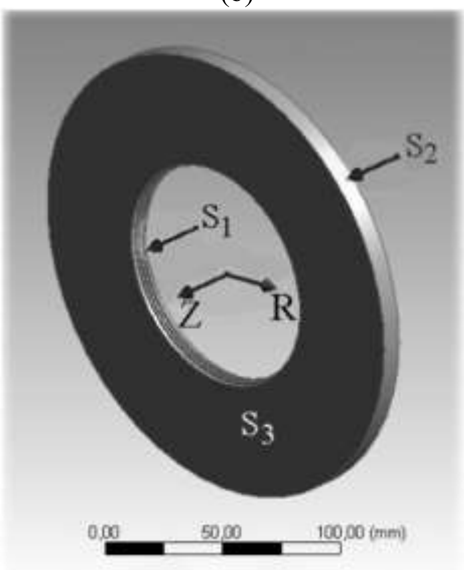
2 Numerical Simulations

Consider a cylindrical vortex chamber of the first type (Figure 1a). Here S_1 is the inlet surface of the chamber (the side surface of a circular cylinder with a diameter of 204 mm and a height of 15 mm), through which the reacting gas flows through the nozzles from the collectors into the chamber, and S_2 is the surface of the gas outlet from the chamber (a circle with a diameter of 40 mm). S_3 is the side surface of the central nozzle of the chamber (a circular cylinder with a height of 42 mm along the z-axis), which serves to release products into the atmosphere. All external surfaces of the vortex chamber except S_1 and S_2 are rigid, impermeable walls. The z-axis is directed along the axis of symmetry of the camera, and the r-axis is normal to the z-axis.



(a)

(b)



(c)

Fig. 1: Camera diagram.

The second type of chamber is an annular cylinder with a diameter of 40 mm (Figure 1b). The length of the camera (L) is a variable value. The Z axis is the axis of symmetry of the cylinder. The combustion of the mixture occurs in a narrow annular channel at the outer surface of the chamber with a diameter of 5 mm. Oxygen was supplied to the chamber from the receiver through surface S_{11}. Fuel was supplied inside through nozzles on surface S_{12}. S_2 is the surface of the gas detonation product exiting the chamber. The incoming gas is hydrogen with oxygen, and the fuel and oxidizer enter the chamber separately and are already mixed inside the chamber. All external surfaces of the camera except S_{11}, $S_{12,}$ and S_3 are rigid, impermeable walls. The z-axis is directed along the axis of symmetry of the camera, and the r-axis is normal to the z-axis.

The third type is a flat axisymmetric disk (Figure 1b) with an inner diameter of 100 mm (an empty hole in the middle) and an outer diameter of 200 mm. The chemical reaction zone is a volume between two flat rings (S_3 surfaces), the distance between them is 10 mm. The surface S_1 is a wall on which three round inlet openings are located. The middle slot is the inlet nozzle for the oxidizer (oxygen), and the other two slots are the inlet nozzles for fuel (hydrogen). The surface S_2 is the output zone of the chamber (the output of detonation products into the open space). S_3 surfaces are the walls of the chamber. The Z axis is the axis of symmetry of the body, and the R axis is at right angles to the Z axis. The combustion of the mixture takes place inside the chamber. Oxygen is supplied to the channel from the receiver through a gap in surface S_1. The total area of the nozzle is 61 mm^2. Fuel was supplied through the nozzle to the same surface S_1. The total area of the nozzle is 35 mm^2. Fuel and oxidizer enter the chamber separately and are mixed already inside the chamber.

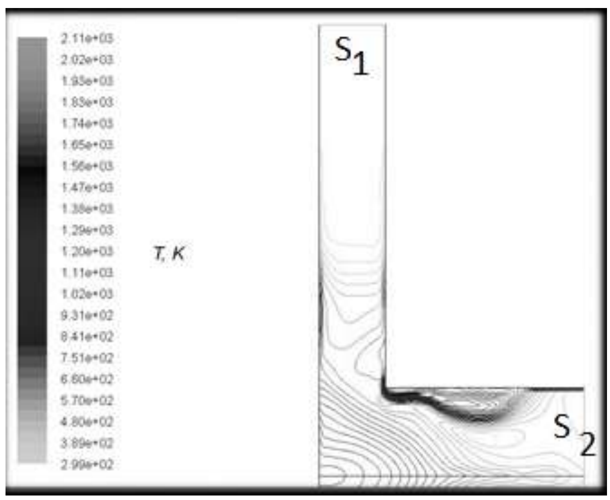


Fig. 2: Map of isotherms for the gas flow in the chamber of the first type.

For all chambers, initially, the internal volume of the installation is filled with nitrogen at an initial gas pressure of p_0 = 1 atm and a temperature of T_0 = 300 K. The initial velocity of the medium has zero value. The gas in the receivers is at elevated pressure values of 10–30 atm, temperature T_0 = 300 K, and zero velocity. The jets of oxygen and hydrogen are directed at an angle to each other for better mixing of the components. At the initial time t_0 = 0, the valves are removed and the gas flows from the receivers into the chamber. The detonation was initiated by the concentrated release of energy in the mixing zone. It is necessary to determine the values of the gas parameters in the chamber after ignition at $t > 0$.

The geometrical parameters of the installations and the nature of the boundary conditions make it possible to model the flow within the framework of the axial symmetry approximation. The flow of a viscous heat-conducting compressible medium inside the chambers was described by non-stationary two-dimensional Reynolds equations for the laws of conservation of mass, momentum, and energy, taking into account the effects of turbulence. Changes in the mass concentration of components of a chemically reacting gas mixture were determined using Fick's second law for diffusion in multicomponent mixtures. The model of chemical reactions is based on a two-stage model of chemical kinetics for the average molecular weight of a gas, including ignition delay. The problem posed above was solved numerically using the large particle method. For verification of the numerical algorithm and to check solution stability, test simulations were made for various sizes of numerical cells using the Fluent program. The comparison of results shows the reliability of our study. A detailed mathematical formulation of the problem can be seen in, [5], [6].

The energy supply to the detonation initiation chamber should be carried out when, as a result of turbulent mixing, an area with the necessary parameters of a combustible gas mixture arises, and heat generation in the zone of chemical transformations is mainly determined by the rate of turbulent mixing of reacting gas components.

Figure 2 shows the cross-section of the chamber of the first type at time $t = 1.4\cdot10^{-3}$ s from the beginning of the mixture supply to the chamber. The flow moves from above here, and the output of combustion products occurs to the right. Note that at this point in time, there has not yet been a concentrated supply of energy to initiate detonation. Nevertheless, due to the complex geometry of the rigid walls of the channel, "hot spots" are formed in the boundary layers - local areas where the gas temperature significantly exceeds the ignition temperature Tig = 1200 K, while the bulk of the gas in the chamber remains quite cold. Such spontaneous ignition of the mixture disrupts the optimal mode of operation of the camera and creates technological problems.

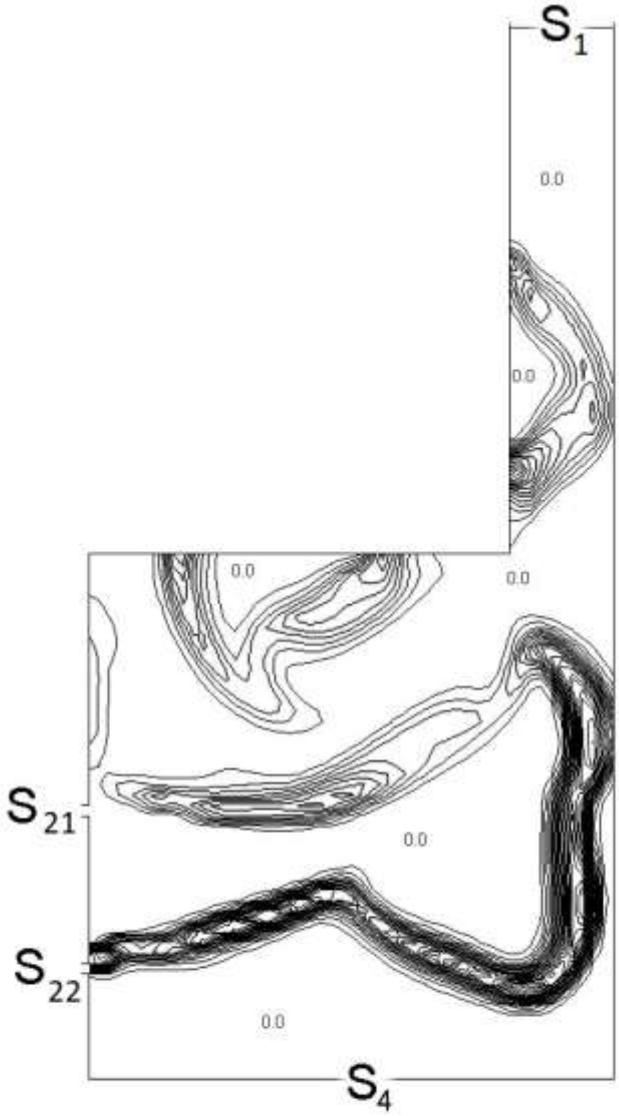


Fig. 3: Map of the chemical reaction rate (kg·moll/(m^3 s)) at the instant $t = 2.5\cdot10^{-3}$ s.

Let the flow in the chamber of the first type move in the opposite direction (Figure 3). S_1 is the surface of the exit of combustion products, and S_2 is the entrance of reagents into the chamber. Here, S_{21} is a slit through which a jet of oxygen enters, and S_{22} is a jet of hydrogen. S_4 is the axis of symmetry of the chamber. It can be seen from the figure that a stagnant zone is formed in the upper left corner of the chamber, where the nitrogen concentration decreases slowly. Heat generation in this zone is low, the turbulent flame practically stops due to the low concentrations of reacting components. This mode is also not an optimal technological mode.

Consider the gas dynamic flow in an annular chamber of the second type (Figure 4). Here, the combustion of the mixture occurs in a narrow annular channel at the outer wall of the chamber, the channel width is 5 mm. Oxygen was supplied to the channel from the receiver through surface S_{11}. Fuel was supplied inside through nozzles on surface S_{12}. S_2 is the surface of the gas detonation product exiting the chamber. One of the features of the flow in this chamber is the formation of an area of increased pressure near the surfaces S_{11} and S_{12} when oxygen and hydrogen jets collide. Moreover, the gas pressure in the area may exceed the pressure in the receivers, leading to a temporary blocking of the flow and the cessation of the flow of reagents into the chamber. As a result, the detonation is disrupted, and, consequently, the output is suboptimal. In addition, the zone of chemical transformations with heat release is located in the center of the channel. Therefore, the jets of unreacted oxygen and hydrogen are pressed against the walls of the channel and move in the direction of surface S_2. At the same time, a significant part of the unreacted mixture (up to 30%) leaves the chamber through the S_2 surface. This reduces the efficiency of fuel combustion in such a chamber.

Now let's look at the picture of chemical transformations in the chamber of the third type (Figure 5). Reagents are supplied to the chamber through annular slots on surface S_1. Through the middle slit, a jet of oxygen enters at right angles to the surface, through the other two slits, there are hydrogen jets at an angle of 450 to the surface. This position of the jets allows for a more intensive mixing process and the formation of a combustible mixture. It is shown that the zone of chemical transformations occupies a more significant part of the camera than the second type of camera. Moreover, a secondary flame front is located at the exit surface S_2, which ensures that the mixture burns out inside the chamber. This mode seems to be the most optimal compared to the previous ones.

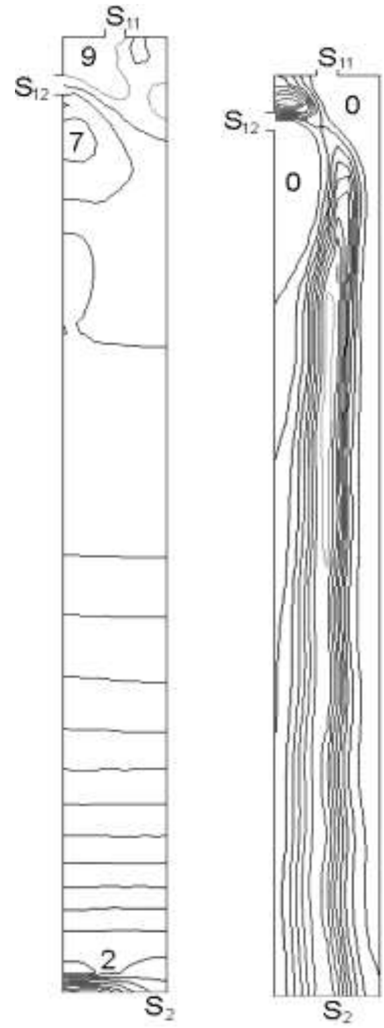


Fig. 4: Pressure field (left, there) and water vapor concentration distribution (right) in the second type chamber at $t = 3.0 \cdot 10^{-3}$s.

3 Conclusions

In combustion engines, the process of fuel burning at constant pressure is usually used. An important technological task is the use of a detonation method of fuel combustion with the formation of shock waves, which leads to an increase in the efficiency of the engine. One of the goals of this paper is to determine the effective and optimal types of combustion chambers to develop detonation processes.

A comparative analysis of geometrically different types of combustion chambers is carried out based on the initial stage of the formation of the detonation process in a gaseous hydrogen-oxygen mixture. It is shown that the most optimal detonation combustion mode occurs for the geometrically simplest type of chamber – a plane radial disk.

Present investigations concern the triggering of detonation processes in combustion cameras. The next stage of our study will be simulations of stable self-supported spin detonation in camera for various types of combustion mixtures (not only the hydrogen-oxygen case).

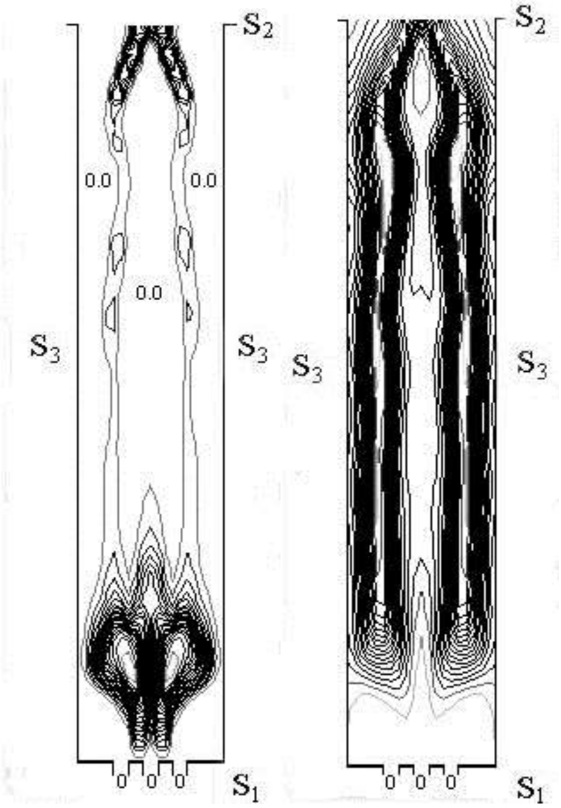


Fig. 5: Distribution of water vapor concentration (left) and chemical reaction rate (kg·moll/(m^3 s)) at the instant $t = 2.5 \cdot 10^{-3}$ s for the third type chamber.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)
The author contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest
The author has no conflicts of interest to declare.