INTRODUCTION

In the investigation of combustion of chemically active gas mixtures, the prediction of maximum pressures, which may occur during the explosion development in bounded volumes, in particular, within combustion chamber of engines or within buildings filled by combustible gaseous mixtures, is topical. Detailed analysis of the development of various combustion modes is required during the development of new and presently existing technical systems, the operation of which is based on effective burning of air–fuel mixtures, and is necessary to choose reasonably criteria and measures for prevention of operation risks [1] of industrial objects, which are potentially subjected to the risk of breakage as a result of the development of chemical explosions.

After initiation, combustion in volumes filled by combustible gaseous mixtures may develop in various ways: combustion quenches; the slow or fast combustion wave propagates over the combustible mixture; transition from the subsonic combustion mode to detonation (DDT) is realized; and detonation excitation is possible as a result of an additional extraneous effect (local intensive energy release, strong shock wave, etc.). At the same time, equally with the detonation mode, a definite hazard lies in fast nonstationary combustion, which uninterruptedly generates compression waves and weak shock waves dynamically loading the shell of the closed volume.

The occurrence of either combustion mode depends on quite a number of partial conditions formed in the ambient medium. We know mechanisms of flame acceleration and detonation formation that are related to the additional excitation of the combustible medium and the formation of nonuniform flame codirectional or counter-current flows as a result of the effect of shock waves (SW), which are generated by the front itself [2–5] or produced artificially by extraneous sources [6–10]. Under the action of the shock wave on the front of the accelerated flame, the time for transition to detonation can be shortened as a result of the additional flame acceleration in the compressed combustible substance heated behind the shock wave or because of the development of nonlinear hydrodynamic processes of the type of the Darrieus–Landau and Richtmyer–Meshkov instabilities. Note that the flow may remain laminar. The transition to stationary detonation may occur as a result of preliminary compression and heating via the stage of the nonstationary over-compressed mode with a relative increase in pressure at the front [8]. The formation of these non-stationary overdriven modes of detonation against the background of the preliminary loading and heating of the medium by compression waves and weak shock waves traveling ahead seems to be one of the most dangerous factors leading to the destruction of constructions. At the same time, as it was shown in [9], the characteristics of the appearing detonation mode are determined by individual features of the development of the transient process, the analysis of which requires elucidation of the mechanisms of the interaction of the flame with shock waves and the formation of detonation.

In article [10] the numerical simulation method is used for investigation of the problem of the interaction
of the shock wave with the combustion zone in a rectangular channel, one end of which is opened (shock wave input) and the other is closed with a rigid wall. The channel was filled by an air–acetylene or air–ethylene mixture at a pressure of 0.1 atm. The combustion source was given at some distance from the closed end. The kinetics of chemical reactions was determined by the simplest Arrhenius equation with specially fitted constants. In the article, they considered only one DDT mode caused by shock waves. Computations showed that detonation in the air–acetylene mixture occurs in waves that are re-reflected from the closed end and outrun the leading front of the flame. The question arises as to whether the results in [10], which are obtained using simulation subject to simplified computer models, are general. The explanation of the physical mechanisms of DDT is based on the formation of detonation in “hot spots.” However, in [9, 11, 12] the authors showed that this DDT mechanism was nonunique and not most general for the chemically active media, to which, apart from the oxygen–hydrogen mixture [11, 12], acetylene- and ethylene-based stoichiometric mixtures can be related. Moreover, from the subsequent additional analysis of computation results represented in [9], it follows that the DDT mechanism in “hot spots” is the product of the complex interference of re-reflected waves and is realized in a relative narrow range of intensities of the incident shock wave.

The problem of the effect of the shock pulse duration on the process development seems practically significant. The shock wave in [9, 10] was simulated by an infinitely extended pulse that eliminates the features of the flame development in the rarefaction area behind the shock wave, where the expansion factor, which promotes the development of the hydrodynamic instability of the flame front and its additional acceleration, becomes leading.

The present research is devoted to detailed investigation of the mechanisms of detonation formation and high pressure generation as a result of flame interaction with a shock wave in a bounded volume filled by a hydrogen–based combustible mixture. The dependence of appearing ultrahigh pressures on the intensity of the external shock-wave action and the detonation formation mechanism is investigated in detail. The choice of hydrogen as the fuel is determined by its center role both in problems of the estimation of safety in the cases of severe accidents on nuclear power plants [1] and in problems of the determination of the energy efficiency for utilization of hydrogen as a fuel for promising engines. In addition, the hydrogen oxidation reaction is the most striking representative of a chain reaction of combustion that makes it possible to propagate the main patterns obtained in the research to a wider range of combustible mixtures.

STATEMENT OF THE PROBLEM

In the present research we investigate numerically in the two-dimensional plane geometry the interaction of a shock wave with a flame in semi-opened channels, which are filled by stoichiometric oxygen—hydrogen and air—hydrogen mixtures under normal conditions (pressure of 1 atm, temperature of 300 K). The investigation is carried out in formulation [9] closed to that accepted in [8, 10]. We consider a half-opened channel, the left end of which is closed, and the opposite opened end of the channel receives the shock wave. The fuel ignition is given at a distance of 13 cm from the closed end by increasing the combustible mixture temperature in a small area on the channel axis up to 1200 K at normal pressure, which corresponds to soft ignition of the mixture with an induction time of 18 µs (oxygen—hydrogen) and 43 µs (air—hydrogen). Further, processes of transfer determine the formation of the flame front at the boundary of the area of the heated expanded gas and its subsequent propagation over the combustible mixture. The tests performed earlier (see [12] and other papers of these authors) show that this approach reproduces well the formation of the quasi-stationary flame and its characteristics in the absence of additional external factors. This determines the initial stage of the development of combustion in the channel and makes it possible to attain fast enough and smoothly the interesting quasi-stationary combustion mode in computations. The shock wave front is given by the step of thermodynamic parameters at a distance of 30 cm from the closed end of the channel and propagates in the direction to the ignition source. At the initial time, the parameter step at the shock wave front is computed based on the Hugoniot relationships at the given Mach number of the shock wave. The numerical simulation is carried out for flame interaction both with the shock front of the infinite extended pressure pulse and with the pulse of the finite duration. The infinite extended pulse can be generated by a high-pressure chamber with a large enough volume. In this case, the flow behind the shock wave front is directed in the direction opposite to the leading (right) flame front up to the time of the shock wave reflection from the closed end. In the case of the finite extended pulse, the shock wave is given by the initial rectangular pulse with a given extension so that the wave propagates with constant velocity to the point of meeting with the leading flame front. The pulse therewith gains a triangular shape as it propagates over the medium. In this case, the leading flame front stretches after interaction with the shock wave further in the rarefaction area behind the shock front. Note that the shock front, as it approaches the leading flame front, turns out to be somewhat distorted because it in passing crosses with weak compression waves generated by the flame, which is expanded from the ignition area.

The slip boundary conditions are given at the side walls of the channel that eliminates the factor of the interaction of the flame and the shock wave with a viscous boundary layer and makes it possible to consider the shock—flame interaction separately from other additional factors. The side channel walls were given as