NUMERICAL STUDY OF EFFECTS OF MOLECULAR TRANSPORT PROCESSES IN GAS-DETONATION WAVES

A. V. Trotsyuk, M. S. Ivanov

Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, 630090, Novosibirsk, Russia

Introduction

Recent years have displayed intense development of experimental investigations, numerical simulations, theory and models of explosive behavior in very small geometries (so called microdetonics). Explosives can be gaseous mixtures, liquids, and solids. Some researchers define microdetonics as the study of less-than-CJ (Chapman-Jouguet) detonation performance due to curvature and/or transient behavior, and substantial losses of momentum and energy from the reaction zone in detonation waves (DWs). The reason is a significant effect of transport processes (viscosity, heat conductivity, and diffusion) on the flow structure in detonation waves at microscopic scales (low Reynolds numbers).

In particular, the propagation of DWs in the near-limit regime through smooth narrow channels and porous media attract significant attention of researchers. The reason is not only the inadequate knowledge of the wave structure under such conditions but also the fact that the existence of this detonation combustion mode is registered under conditions where propagation of classical waves of multifront (cellular) detonation is impossible. In terms of applications, these studies imply reconsideration of detonation combustion limits and are closely related to problems of safety in chemical industry (new micro-reactor technology) and mining.

Another reason that inspired the interest in studying near-limit DWs is the development of the MEMS (Micro-Electro-Mechanical-Systems) and NEMS (Nano-Electro-Mechanical-Systems) technology in the last decade. It became necessary to create devices for realization of combustion at scales much smaller than previously explored. By considering micro-devices able to produce mechanical work from chemical heat release, we conclude that characteristic time scales associated with heat loss mechanism are reduced drastically when the scale of devices decreases. At the same time, the characteristic time scales for heat release, governed by the deflagration processes (flames) stay fairly independent of scale. This means that, when conventional devices such as internal combustion engines and gas turbines are scaled to miniature sizes, their efficiency is degraded seriously. The heat is being lost faster than it is being produced, in addition to proportionally more important frictional effects as well. To solve this problem, the most promising possibility is the use of the detonation mode of combustion since very rapid material and energy conversion is the key feature of detonations. In addition, MEMS and NEMS safety is also a topic that requires intense investigations.

All this provides a strong motivation for investigation of different microdetonics problems using more complete flow models and advanced numerical approaches.

Nevertheless, such studies require a special tool, namely, a numerical code capable of operating on advanced multiprocessor clusters. To examine shock wave-boundary layer interaction, one needs a high spatial resolution, which necessitates the use of an extremely fine numerical grid in the region of interaction. As a result, the volume of computational operations and the computational time increase. The only way out is the development of a parallel numerical code for modeling multidimensional reacting viscous flows in micro-scales.

The main objective of the present work is the development and verification of such a code and using this code for numerical investigations of viscous detonation flows. The main process to be
carefully studied in the phenomenon considered is the interaction of the boundary layer growing on the channel walls behind the leading shock front of the DW with transverse waves that form the multifront DW structure.

The Euler equations are used to describe continuum dynamics in most studies on numerical simulations of a multifront (cellular) DW structure in gases. Nevertheless, there are some papers [1-4], where the effect of viscosity (and other transport phenomena) on the DW structure was considered with the use of the Navier-Stokes equations chosen as the governing equations. In the majority of the papers cited above and some others, however, periodic boundary conditions or conditions of free-slip solid walls were imposed on the computational domain boundaries, and these conditions do not imply boundary-layer formation on the upper and lower walls of the channel. High-velocity reacting flows with boundary layers on the channel walls were numerically studied in [3-4]. Interaction of a shock wave reflected from the closed end of the channel filled by a reacting mixture with a boundary layer, which was formed earlier on the channel walls behind the front of a shock wave incident onto the closed end of the channel, was considered in [3]. The influence of molecular transport processes on the DW structure in a hydrogen-oxygen mixture was studied by means of two-dimensional numerical simulations [4]. The computations were performed for rather wide channels \( H \approx 4a_0 \), where \( a_0 \) is the detonation-cell size. Adiabatic boundary conditions on the solid wall were imposed in the publications considered [3,4]. In contrast to these works, the condition of an isothermal wall was used in the present study, because we believe that it is more consistent with the physical processes of DW propagation in the channel. Moreover, the cell size \( a_0 \) obtained numerically in [4] was appreciably (by more than a factor of 1.5) smaller than the value measured for this mixture in experiments. The numerical experiments described here may be considered as a continuation of [4,5], where the problem of interaction of a boundary layer with a cellular detonation structure was formed and the first progress in studying this problem was achieved. We used a more realistic model of chemical kinetics, and the detonation-cell size obtained is in good quantitative agreement with experimental data for hydrogen-oxygen mixtures. The computations were performed with a better spatial resolution on multiprocessor supercomputers; a reliable advanced numerical scheme was used in simulations.

### Formulation of the problem and physical model

A plane rectangular channel filled with explosive mixture is considered. The DW is initiated in the vicinity of the left closed end of channel. The dynamics of the compressible medium was described by two-dimensional unsteady Euler and Navier-Stokes equations. Chemical transformations in the gas mixture were described by a two-step reaction model (including the induction step and the heat release step) [6]. The first (induction) stage was simulated in accordance with the experimental kinetics [7].

After the induction period, the stage of heat release was described using the model of generalized kinetics of chemical reactions at high temperatures [8,9] and the caloric equation of state [9], correlated with the adopted kinetic model with allowance for the second law of thermodynamics. We note that the proposed approach makes it possible to take into account substantial variations in the values of the mean molar mass of the mixture, heat release, specific heats, and their ratio in the course of chemical reactions. This model is approximate but has a high accuracy in description of the heat-release stage, which is commensurable with the accuracy of the detailed kinetic mechanism of chemical reactions. The indisputable advantage of this model is its simplicity, which decreases computer-performance requirements by orders of magnitude. For hydrogen-based mixtures, the use of this model does not require any additional efforts. Implementation of these kinetic models is described in more details in [10]. The system of equations was closed by the thermal equation of state for an ideal gas.
To describe the transport coefficients as functions of temperature, we used a simple dependence of the form $\mu = \mu_0 T^n$, where $\mu$ is the molecular viscosity and $\mu_0$ is a constant. The same dependences were used to calculate the thermal conductivity $k$ and $\rho D$, where $\rho$ is the density and $D$ is the diffusion coefficient. The nondimensional Lewis Le, Prandtl Pr, and Schmidt Sc numbers were assumed to be constant and equal to unity: $Le=Pr=Sc=1$.

**Numerical method**

The resultant systems of equations were solved numerically using the finite-volume scheme [11]. To compute the inviscid fluxes on the volume interface, we used the fourth-order MUSCL TVD reconstruction [12] and the advanced HLLC algorithm [13] for an approximate solution of the Riemann problem. In implementation of this algorithm for the case of a chemically reacting mixture, the “energy relaxation method” [14] was used. This method eliminates the problem of numerical solution of the Riemann problem for a medium with a complicated nonlinear equation of state (including that with a variable ratio of specific heats). Viscous numerical fluxes were also computed in a conservative manner according to [15]. Integration in time was performed with second-order accuracy by using recently developed additive semi-implicit Runge-Kutta methods [16]. The use of adaptive moving grids with local refinement in the vicinity of a leading shock front allowed us to have a fine resolution where necessary, using a significantly smaller number of cells, as compared with a uniform splitting of the computational domain. The time step was determined at each time layer of the solution from the stability condition [11]. In the present simulations, the values of the Courant number were $CFL=0.3–0.4$.

The code is parallelized with MPI library using the domain decomposition technique. Two approaches were used. For a comparatively small number of processors (up to 20), the entire computational domain is decomposed into equal subdomains along one of the axes according to the number of CPUs used in the computation. For a greater number of processors, this procedure is no longer optimal, and the domain decomposition was performed with respect to two coordinates ($x$
and \( y \). The data exchange is performed only between the adjacent subdomains for three halo cells from each side. Although simple, this parallelization technique yields good results in terms of parallel efficiency and scalability.

**Results of computations**

As a first step, we studied the 2D multifront flow structure and characteristics of detonation waves in hydrogen-oxygen gas mixtures propagating in plane rectangular channels in the inviscid case (Euler equations). The validation criterion was the agreement of numerical results on the detonation cell width with experimental data in a \( 2H_2+O_2+X \% Ar \) mixtures. The \( DW \) structure in this mixture with \( X = 0, 50, 60, \) and \( 70 \% \) was numerically studied in the present work with the use of either a usual single-processor numerical code or a parallel numerical code within a wide range of initial pressures from 0.0866 to 0.5 bar. The data obtained on the detonation cell size and its shape demonstrate good quantitative agreement [10] with experimental data [17,18].

The influence of viscosity (and other processes of the molecular transport) on reconstruction of the multifront (cellular) structure of a \( DW \) propagating in a plane wide (the channel width \( H \) is greater than or commensurable with the detonation cell size) channel (see Fig. 1−Fig. 4) was considered. The computations were performed for a \( 2H_2+O_2 \) mixture with an initial pressure \( p_0 = 0.4 \) bar and initial temperature \( T_0 = 288.15 \) K. The computations were performed on a grid with the number of cells \( N_x = 1000 \) and \( N_y = 1000 \) in the \( x \) and \( y \) directions, respectively. The grid in the direction of the channel width (\( y \) axis) was uniform and stationary. In the \( x \) direction, we used a uniform moving grid with 800 cells in the vicinity of the leading shock front; the \( x \) size of the computational cell was equal to its \( y \) size. The remaining 200 cells along the \( x \) axis formed a nonuniform moving grid, which occupied the remaining part of the channel beyond the uniform grid up to the closed end of the channel with \( x = 0 \). 50 CPUs are used.

Figure 1 shows the computed multifront (cellular) \( DW \) structure in this mixture under the above-given initial conditions in the inviscid case (Euler equations). In the case illustrated in Fig. 1a, the channel width \( H = 0.22 \) cm is exactly equal to the detonation-cell width \( a_0 \). In this case, there is a pair of symmetric transverse waves (TWs) of identical intensity on the leading shock front of the detonation wave. Figure 1b shows the changes in the multifront \( DW \) structure observed if the channel width \( H = 0.24 \) cm is slightly greater than the cell size \( a_0 \). In this case, there are three almost identical TWs instead of two. As a whole, such a jumplike change in the number of transverse waves on the \( DW \) front induced by a small change in the channel width is consistent with experimental observations for gas mixtures with a regular or extremely regular cellular structure. Figure 5d shows a multifront \( DW \) structure in the same mixture for \( H = 0.18 \) cm. The TW symmetry is seen to be violated in a narrow channel (as compared with the channel in Fig. 1a). This violation of symmetry is even more noticeable in the form of different induction-zone widths behind the leading shock wave ahead of the upper and lower TWs. Thus, Fig. 1a, Fig. 1b, and Fig. 5d show the procedure of determining the detonation-cell size (width) in a narrow channel commensurable with the detonation cell in size.

Figure 2 shows an example of detonation computations with allowance for transport phenomena in the gas (Navier-Stokes equations). As is seen from Fig. 2a, the cell size determined by the method described above \( (a_0 = 0.24 \) cm) is slightly greater than the cell size in an inviscid detonation wave \( (a_0 = 0.22 \) cm). Both values, however, rather accurately agree with the experimentally measured cell size in the examined mixture with the indicated initial pressure [12,13]. Figure 2b shows a zoomed-in temperature field (in Kelvin degrees) in the vicinity of the leading shock front, near the upper wall of the channel. An extremely narrow boundary layer on the cold channel wall with a significant temperature gradient in the layer is clearly visible. Figure 2c shows the profile of the streamwise velocity \( u \) (cm/s) and temperature \( (T, K) \) of the gas near the lower channel wall, behind the wave front at the point with \( x \approx 3.92 \) cm, see Fig. 2a. Thus, the flow...
Fig. 2. Viscous detonation (Navier-Stokes equations): (a) numerical Schlieren images of the flow field for a multifront detonation wave in a channel of width $H=0.24$ cm. There are two identical and symmetric transverse waves on the leading shock; (b) Zoom – temperature field, Kelvin degrees, in the vicinity of the leading shock front near the upper wall of the channel, see (a); (c) profiles of streamwise velocity $u$, cm/s, and temperature $T$, K, of the gas near the lower channel wall behind the wave front at the point $x \approx 3.92$ cm, see (a); (d) numerical Schlieren images of the flow field – continued computation of the viscous DW up to the front position $x_f \approx 8.15$ cm. 50 CPUs are used.

structure in the case of viscous detonation possesses high gradients of the gas parameters near the solid walls of the channel. For this reason, a high spatial resolution is required in numerical simulations of viscous DWs for correct modeling of the emergence and growth of boundary layers behind the leading shock wave. It is also necessary to use high-performance multiprocessor
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Fig. 3. Viscous detonation (Navier-Stokes equations) under inviscid boundary conditions (as for the Euler equations). Numerical Schlieren images of the flow field for a multifront detonation wave in a channel of width $H=0.24$ cm for different DW front positions: (a) $x_f \approx 8.9$ cm; (b) $x_f \approx 12$ cm. There are three different transverse waves on the leading shock.

supercomputers: simultaneously with a high spatial resolution, DW propagation to large distances has to be computed to determine the stability of the resultant multifront structure of the DW front. In our research, we normally tracked the DW front structure downstream to distances $x_f=30 \div 50 H$, sometimes, even to greater distances.

Figure 2d shows the DW structure at a distance $x_f \approx 8.15$ cm, which is almost twice the distance covered by the DW in Fig. 2a. By comparing these figures, we see that the multifront structure obtained in this computation is stable and consists of a pair of symmetric TWs on the leading shock wave. In the present paper, stability of the multifront DW structure is understood as its repetition with a characteristic time period and its independence of the distance that the DW passed along the channel. Though the multifront structure with a TWs on the DW front is a shock-wave configuration unstable in time, it has its own characteristic spatial scale (detonation-cell size $a_0$) and an associated characteristic time period.

Figure 3 shows the multifront DW structure in the same channel with $H=0.24$ cm as that in Fig. 2 for different positions of the DW front. Navier-Stokes equations were again used in this numerical experiment. The main difference between this numerical experiment and that in Fig. 2 was the use of different boundary conditions on the channel walls. This was made to elucidate the mechanism of the influence of transport processes on the multifront (cellular) detonation-wave structure in gas mixtures. The following boundary conditions were imposed in the present computation: the transverse gas velocity on the wall was $v=0$ and the wall temperature was equal to the gas temperature (adiabaticity condition). These boundary conditions for the Navier-Stokes equations were conventionally called the inviscid boundary conditions or the conditions identical to those for the Euler equations. In other words, we used the slip condition for gas velocity to eliminate the boundary-layer formation on the channel walls. The condition of adiabaticity was chosen to avoid gas cooling near the wall due to heat conduction. In contrast, the computations in Fig. 2 were performed under the boundary conditions usually used for the Navier-Stokes equations: the streamwise and transverse velocities of the gas on the wall were $u=v=0$ and the wall temperature was $T_w=T_0=288.15$ K (condition of an isothermal wall). Such boundary conditions may be called
Fig. 4. Viscous detonation (Navier-Stokes equations) with the molecular transport coefficients reduced by a factor of 1000 (thousand). Numerical Schlieren images of the flow field for a multifront detonation wave in a channel of width $H=0.24$ cm. Different boundary conditions on the channel walls: (a) viscous conditions. There are two identical and symmetric transverse waves on the leading shock; (b) inviscid boundary conditions (as for the Euler equations). There are three transverse waves on the leading shock.

Thus, by comparing the results of numerical simulations plotted in Fig. 1, Fig. 2, and Fig. 3, we see that the influence of transport processes on the multifront (cellular) DW structure in gases is primarily manifested in formation of viscous boundary layers on the channel walls. Apparently, TW interaction with these layers alters the conditions of reflection of these waves from solid walls, which changes the overall shock-wave pattern of the flow (cf. Fig. 2 and Fig. 3). Meanwhile, the momentum and energy losses in a rather wide channel (commensurable in size with the detonation-cell width $a_0$ or wider) do not yet affect the steadiness of the detonation process as a whole.

To check the assumption about the local influence (through boundary-layer formation) of transport phenomena on the DW structure, we performed computations with the constants in the transport coefficients reduced by a factor of 1000 (one thousand). The computed results are plotted in Fig. 4a (viscous boundary conditions) and in Fig. 4b (inviscid boundary conditions). With such a drastic decrease in the values of the transport coefficients, we could reasonably expect the shock-wave pattern in the DW flow to be similar to that in the case of inviscid detonation (Euler equations), Fig. 1b. As is seen from Fig. 4a, however, in the case of formation of boundary layers

the viscous boundary conditions. The choice of the boundary conditions did not affect the diffusion process, because the wall was considered to be non-catalytic in both cases. The difference in the boundary conditions did not affect the transport processes in the internal part of the flow in the detonation wave in the two cases considered here either.

The multifront DW structure in Fig. 3 is essentially different from that shown in Fig. 2. There are three almost identical TWs on the front. As a whole, the flow pattern computed here is similar to the shock-wave pattern in Fig. 1b. The result of allowance for viscosity and other transport phenomena was only the difference in minor details of the flow. There are three TWs on the DW front in computations of both viscous and inviscid DWs in the channel of the specified size. Figure 3 shows the DW front structure at different distances covered by the DW. Based on these results, we can conclude that a stable shock-wave configuration with three TWs on the front was obtained in the case considered.
Fig. 5. Numerical Schlieren images of the flow field for a multifront detonation wave in a channel of width $H=0.18$ cm. Viscous detonation (Navier-Stokes equations), different DW front positions: (a) $x_f \approx 11.16$ cm; (b) $x_f \approx 16$ cm; (c) $x_f \approx 22$ cm. (d) for comparison, inviscid detonation (Euler equations). 100 CPUs are used.

on the channel walls, we still have structures with two TWs, as in the case with standard values of viscosity and other transport coefficients, Fig. 2. The changes in the constants affected only the fine details of the flow behind the DW front; in this sense, the flow resembles the pattern in Fig. 1.

Numerical simulations in Fig. 4 were performed on the same computational grid with $N_x =1000$ and $N_y =1000$. It seems that an even finer grid is needed for the accuracy of boundary-layer computations to be retained with such a large change in the constants in the transport coefficients. Possibly, the boundary-layer structure in these computations was insufficiently resolved.
Nevertheless, the mere existence of the layer on the walls or the absence of the layer induced significant changes in the overall shock-wave structure of the flow in the DW front, as is seen from a comparison of Fig. 4a and Fig. 4b. The flow structure in Fig. 4b, both the detailed structure and the global structure (three transverse waves on the front) is almost the same as that predicted by the Euler equations, Fig. 1b.

Thus, the governing effect on the number of TWs on the DW front in the channel with the width used is exerted by the absence or presence (owing to viscosity and other transport phenomena) of boundary layers on the channel walls rather than the absolute values of the transport coefficients for a particular mixture. The conclusion drawn from the analysis of the numerical experiments described above, which implies that the influence of the molecular transport processes on the global shock-wave structure of the DW flow in gas mixtures in wide channels is manifested locally, through formation of boundary layers on the walls, agrees with the results of numerical simulations [4].

After that, the structure of the DW front in narrow channels (the channel width $H$ being smaller than the detonation cell size $a_0$) was calculated on the basis of the viscous reacting gas model proposed. In this case, the transport phenomena can affect the detonation process not only through formation of a boundary layer on the channel wall, but also through an increase in the relative momentum and energy losses from the reaction zone in a narrow channel. A high level of losses can affect the DW velocity and even the existence of the self-sustained detonation regime. Experimental data suggest that there are certain limits of DW propagation: in narrow channels whose width is smaller than a certain size, steady propagation of a self-sustained DW is impossible.

The results of numerical simulations of detonation waves in narrow channels are plotted in Fig. 5–Fig. 7. Figure 5 shows a viscous DW in a channel of width $H=0.18$ cm in which the flow with one TW on the front is formed. Figures 5a,b,c show different moments of formation of such a structure for different positions of the DW front. At the early stage, there is a transitional structure with one strong TW and one decaying TW (see Fig. 5a). At later times (at greater distances covered by the DW), there appears a steadily propagating DW with one transverse wave on the front (see
Fig. 7. Numerical Schlieren images of the flow field for a detonation wave in a channel of width $H=0.16$ cm. Viscous detonation (Navier-Stokes equations), different DW front positions: (a) $x_f \approx 5.45$ cm, one transverse wave on the leading shock; (b) $x_f \approx 11.35$ cm, decaying non-reacting shock wave.

Fig. 5b,c). For comparison, Fig. 5d shows a multifront structure of an inviscid DW, which would form in the same channel.

Figure 6 shows the results of simulating detonation in a channel with $H=0.12$ cm, i.e., the width of this channel is half the width of the channel used in simulations plotted in Fig. 2–Fig. 4. In the case of viscous detonation, a decaying non-reacting shock wave is observed already at a moderate distance from the initiation point, see Fig. 6a. The leading shock front and the subsequent heat-release zone are separated. The reaction front travels at a significant distance from the upcoming shock wave and cannot be seen in Fig. 6. The shock-wave front has two extremely weak, decaying, almost acoustic perturbations remaining from blasting of the initial site of detonation initiation. For this channel width, we performed a series of computations with a higher initiation energy than that used in computations for $H=0.18$ cm and $H=0.24$ cm (Fig. 2–Fig. 5), the greatest amplification factor used was 2.7 with respect to simulations with $H=0.24$ cm. In all cases, a decaying detonation regime was obtained. Figure 6 shows simulations of the DW with the maximum initiation energy. Apparently, this channel width is smaller than the critical width for this mixture and this initial pressure of the mixture. Apparently, this channel width is smaller than the critical value for this mixture and this initial pressure of the mixture. A self-sustained detonation regime cannot exist under these conditions. As an example, Fig. 6b shows the structure of a self-sustained DW front in the same channel in the case of inviscid detonation. As it could be expected on the basis of simulation results plotted in Fig. 1, in this case we have a stable DW structure with one TW on the front.

To determine the critical channel width more accurately, we performed viscous computations for $H=0.16$ cm. Figure 7 shows the DW flow structure for different positions of the DW front. As is seen from Fig. 7a, this position of the front ensures a critical (or close to critical) regime. The flow structure is similar to that shown in Fig. 5b,c for a wider channel with $H=0.18$ cm. It is seen, however, that the induction zone behind the leading shock front (especially ahead of the TW front) is wider in this case, and the TW intensity is lower than that in a stable (in the above-indicated sense) detonation flow in a channel with $H=0.18$ cm. Further computations (see Fig. 7b), however,
showed that the detonation regime in a channel of this width is not self-sustained. The front of reactions with heat release and the leading shock wave are again separated. As a result, Fig. 7b shows a decaying shock wave similar to that in Fig. 6a. Thus, the critical width of the channel is somewhere between 0.16 cm and 0.18 cm.

The present computation also demonstrated that it is important to establish the fact of stability of the simulated shock-wave structure of the DW front (cf. Fig. 7a and Fig. 7b). It is necessary to compute DW propagation as far as possible, especially in studying the critical regimes of detonation: if we finish the computations at the stage illustrated in Fig. 7a, we could make a wrong conclusion about the formation of a self-sustained DW in a channel of this width.

Conclusions

Multiple careful numerical experiments showed that the transport properties near the channel walls rather than in the central part of the flow exert a significant effect on the number of transverse waves on the DW front (detonation cell size). That is, the influence of viscosity (and other processes of molecular transport) on the multifront DW structure is mainly manifested as the formation of boundary layers on the channel walls, which alters the conditions of reflection of transverse waves from the walls. It is this interaction of boundary layers with transverse waves that leads to changes in the DW front structure via formation of a different number of transverse waves (as compared with an inviscid detonation wave) and, correspondingly, to changes in the detonation cell size.

Numerical experiments in narrow channels (the channel width being smaller than the detonation cell size) showed that transport properties under these conditions affect not only the number of transverse waves on the DW front, but also the mere possibility of propagation of the detonation process in the self-sustained regime. Steady-state DW propagation in the near-limit regime in such a channel was studied under the condition that the channel width $H$ is greater than a certain critical value for a particular chemical composition of the mixture and a prescribed initial pressure. The channel width $H$ where this marginal detonation regime (i.e. detonation wave with one transverse wave) occurs in the case of viscous detonation was found to be 1.5 times greater than the channel width necessary for the same regime to occur in the case of inviscid detonation. Decaying regimes of detonation combustion were also obtained. Thus, it was shown that there exists a propagation limit for a given pressure and chemical composition of the mixture in the case of viscous detonation, which is a geometric limit of DW propagation, i.e., there is a channel width such that a quasi-steady self-sustained DW cannot exist in such a channel. This result is consistent with available experimental observations. The numerical simulations showed that a sub-critical regime of propagation of a viscous DW is possible. An interesting situation is observed, where the initiated DW first propagates in the marginal regime over a significant part of the channel, and then the leading shock front and the zone of chemical reactions become separated (termination of heat release behind the wave front). For this reason, the leading shock front transforms to a decaying non-reacting shock wave.

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