Nonideal Detonation Waves in Rough Tubes

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Abstract

Results of investigations of detonation waves in gaseous systems, with friction and heat transfer effects taken into account, are summarized. The analysis applies to detonations in rough tubes. The following flow models in the reaction zone and downstream of it are considered: (1) the bulk heat release model due to self-ignition of the gas behind the lead shock wave; (2) the model of combustion initiated near the wall due to self-ignition in shock waves multiply reflected at the roughness elements (in this case, the major fraction of the mixture burns in a turbulent flame that eventually covers the entire cross section of the tube); and (3) the model of combined ignition, both in the volume and at the tube walls. An analysis of the problem, with due regard for the two types of mixture ignition, points to the existence of a range of parameters where the detonation velocity selection is ambiguous. The experiments conducted in a rough tube with H₂-O₂-N₂ and C₃H₈-air mixtures show that in real conditions only one detonation mode is realized in rough tubes in which the two ignition mechanisms are operative. It is concluded that quasi detonations in rough tubes can be treated with a non-one-dimensional model of the detonation process. The quasi-detonation wave, with a velocity deficit confined between the values characteristic of the two ignition mechanisms in detonation waves, is shown to be unstable. The heat evolution rate in this wave is subject to large-scale fluctuations.

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Introduction

In recent years nonideal detonation regimes have been extensively discussed in the literature devoted to explosion hazard problems. This is because in most real accident situations, the so-called classical detonations did not occur. However, the destruction caused by accidental explosions shows that with the intensity of the pressure waves and their ability to propagate for long distances, the nonideal explosions are comparable to normal detonations.

The difference between nonideal explosion processes and classical detonations is that the former are substantially affected by energy and momentum losses. Deceleration of the combustion products at the duct walls, and heat transfer, may change the propagation velocity and structure of the reactive wave. A rough internal duct surface may drastically alter the conditions of mixture ignition behind the shock front. For instance, if the temperature of the shocked gas is not sufficient for fast ignition, a possibility of local mixture ignition exists because of multiple reflections of the shock waves at the obstacles. Rough walls strongly turbulize the flow behind the wave front. A turbulent flame arises behind the shock front and is stabilized by continuously appearing hot spots at the walls. Unlike the induction zone in a normal detonation wave, this reaction zone pattern only weakly responds to possible gas temperature perturbations. Thus, quasi-steady explosion processes propagating at low supersonic velocities become feasible.

Hence, the losses dramatically alter the flow pattern behind detonation waves and lead to steady-state solutions that pertain to the waves propagating with a velocity intermediate between slow deflagration and normal detonation.

In the present work we studied both theoretically and experimentally the structure and parameters of detonation waves in rough tubes. The specific features of high-velocity detonations with self-ignition of a homogeneous mixture behind the lead shock (Fig. 1) and low-velocity detonations with mixture ignition in shock waves reflected at obstacles (Fig. 2) are considered. The possible mechanism of nonideal wave propagation under real conditions is discussed.

Formulation of the Problem

In the frame of reference attached to the wave front, the equations governing the one-dimensional (1-D) structure of the reaction zone in a steady-state detonation wave propagating in a rough tube are as follows (Zeldovich 1940):

\[
\frac{D-w}{v} = D/v_0
\]

\[
d[p + (D-w)^2/v]/dx = n\sigma/\phi
\]

\[
d[(D-w)(H+(D-w)^2/2)/v]/dx = -nq/\phi
\]

\[
+ n\sigma D/\phi
\]

(1)
where $D$ is the wave velocity; $w$, $v$, and $p$ are the particle velocity, specific volume, and pressure behind the shock front, respectively; $m$ and $\phi$ are the tube perimeter and cross-sectional area; and the subscript 0 refers to the initial state.

The friction force per unit area of tube surface is

$$\sigma = C_{f} w |w| / 2v \quad (2)$$
where \( C_f(x) \) is the local drag coefficient. The form of Eq. (2) was chosen to account for the possibility of a reverse of the sign of the combustion product velocity.

The heat flux to the wall is calculated by the formula

\[
q = \dot{\varepsilon}(T_{\text{st}} - T_{w})
\]

where \( \dot{\varepsilon}(x) = \dot{\varepsilon}Nu/2r \) is the local heat transfer coefficient, \( \dot{\varepsilon} \) is the heat conductivity of the gas, \( r \) is the tube radius, \( Nu \) is the Nusselt number, and \( T_{\text{st}} \) and \( T_{w} \) are, respectively, the gas stagnation temperature and wall temperature. The gas enthalpy is calculated as

\[
H = Q\beta + \gamma p v / (\gamma - 1)
\]

where \( \gamma \) is the ratio of specific heats, \( Q \) is the heat of the combustion reaction, and \( \beta \) is the unburned fraction described by the equation

\[
d\beta / dx = f(\beta, T, \psi_1, \psi_2, \ldots)
\]

\( \psi_1, \psi_2, \ldots \) are the parameters on which the reaction rate may depend.

The solution of Eqs. (1), (4), and (5) with the additional relationships of Eqs. (2) and (3) must meet the boundary conditions:

\[
\begin{align*}
x &= 0 \quad v &= v' \quad p = p' \quad \beta = 1 \\
x &= \infty \quad v &= v_0 \quad p = p_0
\end{align*}
\]

In the boundary conditions [Eq. (6)], we assume that reaction occurs without a change in the mole number. The prime quantities are calculated from the relationships at the leading shock front.

To close the problem we must define the coefficients \( C_f(x) \) and \( \dot{\varepsilon}(x) \). We will neglect to the first approximation the effect of gas compressibility and longitudinal pressure gradient on the flow deceleration at the beginning of the boundary layer, and assume the velocity profile in it to be of an exponential form. One can then obtain from kinematic similarity that \( C_f \approx \left( k_s / x \right)^{2n} \), where \( k_s \) is the equivalent roughness (Schlichting 1951), \( \delta_p \) is the momentum displacement thickness, and \( n \) is the exponent of the velocity distribution law. From the relationship \( C_f / 2 = d\delta_p / dx \), we can deduce \( C_f \approx \left( k_s / x \right)^{2n / (2n+1)} \); when \( n = 0.125 \), we obtain \( C_f \approx \left( k_s / x \right)^{0.2} \).

The proportionality coefficient can be estimated from comparison with the interpolation formula (Schlichting 1951)

\[
C_f = (1.89 + 1.62 \log x / k_s)^{-2.5} \text{ valid for } 10^2 < x / k_s < 10^6.
\]

For \( x / k_s = 10^{-3} \) we find

\[
C_f \approx 0.03(k_s / x)^{0.2}
\]

From Eq. (7) it follows that \( C_f \rightarrow \infty \) when \( x \rightarrow 0 \). Here we encounter the limit of the applicability of the 1-D theory. For the sake of simplicity we consider the drag coefficient averaged over the reaction zone length \( \delta \) (over the zone
where $D = wC$, $C$ being the local acoustic velocity):

$$C_f \approx \frac{\Delta}{4} \approx 0.04(k_s/\ell)^{0.2}$$

(8)

Coefficient $k_s$ is formally determined from Schlichting's formula

$$\lambda = 0.5 = 2 \log \frac{r}{k_s} + 1.74$$

(9)

where $\lambda$ is the hydraulic resistance coefficient for a tube as measured from the pressure drop per unit length in an isothermal flow. For the low Reynolds number inherent in detonations, coefficient $\lambda$ depends only on $r$ and characteristic roughness size. Equations (8) and (9) permit the losses associated with gas deceleration to be estimated if the tube characteristics are given.

In the reaction zone, $\epsilon$ appearing in Eq. (3) is calculated from the formula $\epsilon = 0.029 \eta \Re_{\infty}^{0.8}$ (Kutateladze 1979) valid for $Re_{\infty} > 5 \times 10^5$. Here $Re_{\infty} = \omega w/\nu$ (where $\nu$ is the kinematic viscosity) is the Reynolds number of the flow in a rough duct, and factor $\eta$ accounts for the heat transfer intensification due to vortex flow near the obstacles, and for the increase in the surface area. To make the problem simpler, we assume that $\epsilon \approx \theta_{\infty}$ and express the average heat transfer coefficient in the reaction zone of a detonation wave as

$$C_h \approx \theta_{h} \approx 0.008 \eta \Re_{\infty} \omega w/\nu w_{p} \nu$$

(10)

Here $\theta_{h} = \omega w/C_{p} |w|$, $C_{p}$ is the specific heat of the gas.

There is a difficulty in calculating the gas deceleration and cooling downstream of the reaction zone (where $D = wC$). On one hand, the flow here tends to a steady state; and on the other, its velocity diminishes, which makes the flow laminar. In this situation reasonable physical approximations are needed that reflect the principal qualitative features of the phenomenon. In the case under consideration the effects of heat losses and friction on the detonation velocity are "localized" in the reaction zone. Therefore, application of one or another relations for calculating gas deceleration and cooling in the supersonic flow reign may solely affect its length, which is not of primary interest for the present consideration. For this reason the drag coefficient $C_f$ can for convenience be assumed to be constant and equal to its averaged value in the reaction zone.

When the flow velocity is low, $\epsilon$ tends toward a constant value ($\epsilon_{\infty} = 3.66$). The flow may become totally stagnant ($\nu = C_{p}$) when the gas temperature differs from that of the walls, and this has to be taken into account when considering the second boundary condition ($P = P_{0}$). The simplest assumption that can be made for the supersonic zone with $Re_{\infty} < 5 \times 10^5$ is $\epsilon = \epsilon_{\infty}$, i.e., to ignore the region of intermittence of flow regimes and the region of laminar flow with an enhanced heat transfer.

The problem thus formulated is completely closed provided that the burning law [Eq. (5)] is known. In the following discussion we will determine the main properties of detonation waves propagating in rough tubes using various physical models of the combustion reaction. The boundary
conditions [Eq. (6)] allow the calculation of not only the reaction zone structure in a detonation wave but the detonation velocity eigenvalue $D$ as well. These relationships require no conditions for selection of the detonation velocity other than those that have already been introduced in the established theory for ideal detonations. This was first pointed out in the work of Zeldovich (1940).

When solving the problem, one has to take into account the fact that Eqs. (1) and (5) have a singularity. The two following conditions from Eqs. (1) and (5) must both be met:

$$D - w = C$$  

(11a)

$$-Q \frac{d\beta}{dx} = \frac{\pi}{\phi} \left[ -9 \frac{v}{D-w} - \sigma \left( \frac{v}{\gamma-1} - v_0 - v \right) \right]$$  

(11b)

The second condition implies that at the section where $D-w=C$ an unburned mixture exists (since $d\beta/dx\neq 0$). An analysis shows that the singular point $(\beta_s, p_s, v_s)$ is of the generalized saddle type [subscript $*$ labels the values at the section where Eqs. (11a) and (11b) are valid]. Consequently, the value of $D$ must be determined by means of the trial-and-error method, i.e., by integrating Eqs. (1) and (5) at various magnitudes of $D$ until conditions in Eqs. (11a) and (11b) are met at some flow cross-section $x_s$. The integral curve must eventually come back to the $v = v_0$ and $p = p_0$ state downstream of the singular point $x_s$.

Because of its complexity, the problem must be solved numerically. The fourth-order Runge-Kutta method was employed in the calculations. To check the correctness of the determination of the $D$ value, the integration was performed from the singular point toward the detonation front where the following conditions are met: $v = v', p = p'$, and $\beta = 1$. To improve the accuracy of calculations in the vicinity of the singular point, new variables were introduced: $\beta = \beta' - \beta_s, v = v - v_s$, and $p = p - p_s$.

**Homogeneous Ignition of the Shocked Mixture**

In this section we consider propagation of a detonation wave in which the mixture is ignited homogeneously as a result of its heating behind the lead shock. We will ignore the fact that some fraction of the mixture burns near the wall behind shock waves reflected from the obstacles. The chemical kinetic equation [Eq. (5)] assumes the form

$$d\beta/dx = -k\beta^m \exp\left(-E/RT\right)/(D-w)$$  

(12)

where $k$ is the preexponential factor, $m$ is the reaction order, $E$ is the activation energy, and $R$ is the gas constant.

The calculations were made for the following magnitudes of the main parameters. $C_p$ was varied between 0 and 0.5, and $C_H$ between 0 and 0.05. The $r$ ranged from $2.5 \times 10^{-3}$ to $1.5 \times 10^{-1}$; $m = 0, 1, 2$; $E = 25$ to 40 kcal/mol, and $Q$ was varied from 13 to 15 kcal/mol, while $k$ value was $10^{10}$ s$^{-1}$ and $\gamma = 1.3$. The velocity deficit in all
the calculations was no more than $\Delta D = (D_0 - D) = 0.13D_0$, where $D_0 = [(2\gamma - 1)Q]^{1/2}$ is the ideal detonation velocity.

A calculated $p-v$ diagram for the case $C_f = 0.5$, $C_h = 0.02$, $E = 25$ kcal/mol, $n = 1$, and $D/D_0 = 0.92$ is presented in Fig. 3. In the 1-D case considered, a pressure rise is observed behind the shock front due to the work done by friction forces (when $C_f < 0.2$, the pressure hump is not seen).

Point A in Fig. 3 pertains to the states of the initial mixture behind the shock front ($\beta = 1$). At point B half of the mixture has burned out ($\beta = 0.5$). Point C is the Chapman-Jouguet (CJ) plane wherein conditions in Eqs. (11a) and 11b are fulfilled ($\beta = \beta^* = 6 \times 10^4$), and point G represents the final state of the stagnant and totally cooled combustion products. As seen in Fig. 3, the particle velocity changes its sign in the expansion process, and the specific volume becomes greater than 1. This effect was first explained by Zel’dovich (1940).

Figure 4 shows the detonation velocity as a function of the drag coefficient for different reaction orders and acti-

![Fig. 3 Detonation Hugoniot for a wave with losses and an analog of the Rayleigh line, the bulk ignition case. A. the state behind the lead shock wave; B. the point where 50% of the mixture has reacted; C. the CJ point; and G. the complete stagnation and cooling point. Schematic of the particle velocity dependence on distance in the laboratory frame of references.](image-url)
vation energies. The dotted continuation of one of the curves represents the unstable branch of the solution to Eqs. (1) and (12). From Fig. 4 it is seen that the detonation velocity drops abruptly at a particular value of $C_f$. Such a behavior is typical of the dependence of the experimental detonation velocity on mixture composition, initial pressure, tube diameter, blockage ratio, etc., and is associated with the detonation limits.

In accordance with the estimates made by Zeldovich and Kompaneets (1955), the detonation velocity at the limit drops by a value

$$\Delta D/D_0 = \epsilon \frac{RT'}{E}$$

where $T'$ is the temperature at the shock front and $\epsilon$ is a coefficient. The preceding expression for $\Delta D$ was derived with heat losses alone taken into account. The value of $\epsilon$ is 0.5 in this case.

Friction heats up the mixture additionally, which may extend the detonation limits. In an approach similar to that of Zeldovich and Kompaneets (1955), it can be shown that for

$$w = \frac{(\gamma+1)^2F}{2(\gamma-1)\gamma D_0^2} \geq 1,$$

then $\epsilon = 0.5$.

For the curves of the two families in Fig. 4, $w = 7.3$ and 6.3, respectively, and $\epsilon = 1.5$ and 1.8. Thus, for mixtures with a lower activation energy, flow deceleration results in broader detonation limits. As expected, the calculated $\Delta D$ decreases as the activation energy increases and $\epsilon \geq 0.5$.

The limiting value of $C_f$ (or $\lambda$) at which the detonation still propagates grows as the reaction order and activation energy increase. At a fixed value of $C_f$ (or $\lambda$), the detonation velocity is higher the greater the reaction rate and the smaller the reaction order. As the activation energy increases, the influence of the reaction order on the detonation velocity deficit in a rough tube becomes weaker.

![Diagram](image)

**Fig. 4** Detonation velocity in a rough tube as a function of friction losses (the bulk ignition case). Solid lines are for $E=27.5$ kcal/mol, and dashed lines are for $E=27.5$ kcal/mol. Numbers at the curves represent reaction order.
The heat losses affect the detonation velocity only slightly and are essential solely near the limit (curves 1' and 2' in Fig. 4).

The unburned fraction at the CJ point is low in all the variants calculated and exerts virtually no effect on the detonation velocity. The highest values of \( \delta^* \) were obtained for \( m = 2 \). For instance, with \( C_f = 0.5 \) and \( m = 2 \), the unburned fraction is somewhat higher than 2%. As \( C_H \) and \( C_f \) grow, the unburned fraction increases. In mixtures with a higher activation energy, \( \delta^* \) is smaller at the same \( D \).

An analysis shows that Fig. 4 has a more general meaning than has been indicated above. If a quantity \((C_f/r) \times 10^{-2}\) is plotted along the \( x \) axis in Fig. 4 instead of \( C_f \), the curves will be independent of the tube radius. This is because at \( C_H = 0 \), \( r \) appears in Eqs. (1) and (12) only in the combination \( C_f/r \). Hence, the condition \( C_f/r \) is the same for a given mixture and permits the utilization in large-scale experiments of the data on detonation propagation obtained in laboratory-scale tubes.

Figure 5 shows the detonation velocity vs the reaction heat dependencies for different values of \( C_f/r \). The curves presented in the figure reflect to some extent the detonation velocity vs the mixture composition dependencies, and are in good qualitative consistency with the experimental data (Matsui 1981).

The Model of Detonation with Ignition at the Walls

Experiments by Schelkin (1949) demonstrate that quasisteady explosion processes may propagate at a velocity almost one-half as high as the ideal detonation velocity \( D_0 \). According to the preceding estimates, a stable detonation with self-ignition behind the lead shock wave is impossible in these conditions.

![Diagram showing the relationship between \( D/D_0 \), \( C_f/r \), and \( Q \) kcal/mol.](image)

**Fig. 5** Detonation velocity in a rough tube as a function of the reaction heat for various drag coefficients (the case of bulk ignition).
Zeldovich (1940 and 1955) and Schelkin (1949) have suggested what the mechanism of propagation might be for such a low-velocity detonation in rough tubes. According to this mechanism, the mixture is ignited near walls because of its compression and heating in shock waves multiply reflected from the obstacles. The further mixture combustion takes place in a turbulent flame that emanates from the wall, forming a cone.

We illustrate the aforesaid combustion mechanism using a methane-air mixture as an example. The detonation velocity as a function of the equivalence ratio $\alpha_f$ (solid line) is shown in Fig. 6 (Westbrook 1982). Also presented is the shock wave velocity (dashed line) at which the ignition delay in a wave that has undergone a single reflection at a rigid wall is equal to that in an incident shock wave propagating at the normal CJ detonation velocity.

The limits of the low-velocity detonation in the stoichiometric methane-air mixture in rough tubes are $0.8 < \alpha_f < 1.2$, corresponding to the Mach number interval of 2.98 to 3.45. From the data by Kogarko and Borisov (1960), it follows that the ignition delay for the strongest incident wave from this interval is $t_f = 0.79$ s. Behind the reflected shock waves at $M = 2.98$ to 3.45, $t_f < 10^{-3}$ s.

When simulating the detonation with wall ignition, we suppose that the law of mixture burnout (Eq. (5)) is determined by the growth of the turbulent boundary layer behind the shock front. The temperature in the region of multiply reflected shock waves is assumed to be so high that burning starts immediately behind the wave front. The burning rate

![Fig. 6](image.png)

Fig. 6 The calculated detonation velocity for the two heat release mechanisms in rough tubes (for methane-air mixtures). The dashed line is obtained for the wall-ignition mechanism under an assumption that the ignition delay in the reflected shock wave equals that in the incident wave propagating at the CJ velocity; $\alpha_f$ is the equivalence ratio.
is practically temperature-independent and depends on the turbulence intensity in the boundary layer. The equation for the chemical reaction rate [Eq. (5)] in this case can be written as

$$\beta = n(r-\delta)^2/mr^2$$

(13)

where \( \delta \) is the thickness of the boundary layer. For the sake of simplicity the rate of the boundary layer growth is assumed to be constant, i.e., \( \delta = k_\delta x \). Here \( k_\delta \approx 0.02 \, \text{w} / (\text{D-w}) \) (Zeldovich and Kompaneets 1955).

Calculations were performed for the following values of the basic parameters: \( C_\text{g} \) was varied between 0 and 0.05, \( r \) from \( 2.5 \times 10^{-3} \) to \( 1.5 \times 10^{-1} \) m, \( Q \) between 13 and 15 kcal/mol, and \( \gamma = 1.3 \).

Figure 7 demonstrates a calculated p-v diagram for the detonation regime with wall ignition (similar to that in Fig. 3). The characteristic points have the same meaning as in Fig. 3. The unburned fraction at point C (CJ point) is \( \beta = 0.1 \). The reaction zone length is large in the case considered (5 to 10 tube radii).

The detonation velocity as a function of coefficient \( C_\text{g} \) is plotted in Fig. 8. As can be seen, the losses caused by the deceleration and cooling of the reacting gas can reduce the velocity of a self-sustained detonation by a factor of two compared with its ideal thermodynamic value.

Figure 9 presents calculated profiles of the gas temperature averaged over the tube cross section. As the blockage ratio of the duct increases, the temperature in the reaction zone changes only slightly, despite the fact that the detonation velocity drops by a factor of two. This is
associated with the transformation of part of the kinetic energy into friction heat, which compensates for the temperature drop caused by lower velocities of wave propagation. Such a temperature variation pattern may be one of the reasons for low values of detonation velocities at which the wave in rough tubes still propagates steadily.
Fig. 10 The unburnt fraction as a function of the momentum and heat losses. The detonation regime with a mixed heat release.

The basic property of detonation in a rough tube is incomplete mixture burning in the reaction zone. The unburned fraction increases as the drag coefficient grows and may reach more than 20% (Fig. 10). Due to this phenomenon, thermodynamic calculations can no longer give any idea of how large the detonation velocity is in a system with losses unless the real flow pattern in the reaction zone is taken into account. Incomplete mixture burning in the CJ plane may additionally diminish the wave velocity by more than 10%. Note that occurrence of the reaction downstream of the CJ plane may have no effect on the detonation wave propagation, since the flow in this zone is supersonic.

However, incomplete burning of the mixture in the reaction zone may also bring about multifront detonations. Burning of the mixture in the supersonic zone of the flow leads in this case to appearance of infinite derivatives of the thermodynamic parameters and gas velocity; as a consequence, the continuation of the solution to the final state becomes impossible. Such a situation can be connected with generation of secondary shock waves behind the lead shock front. The unburned mixture behind the primary CJ plane may burn out behind the secondary waves; thus, several CJ planes may arise in the flow. Mixture burning behind subsequent detonation fronts is represented in the p-v diagram by the discontinuous curve.

One-dimensional calculations yield a qualitatively correct prediction of the detonation velocity drop caused by a decrease of the diameter of a rough tube. Figure 11 displays $D(r)/D_0$ curves for $C_f = 0.006$ and various $C_h$ values. It can be seen in Fig. 11 that, when $C_f = \text{idem}$ and $d > d_{cr}$
Fig. 11 Detonation velocity as a function of the tube diameter for various drag coefficients (the wall ignition model).

\( d_{CR} \) is the critical diameter for detonation propagation in a duct, the \( D \) is virtually independent of the tube diameter. This implies that, in tubes of different diameters having geometrically similar roughness, the low-velocity detonation processes in mixtures of the same composition propagate with nearly the same velocities. This property may be considered a condition for geometric modeling of low-velocity detonations. To verify the criterion, the data of Peraldi et al. (1986) are used in Fig. 12.

Fig. 12 Detonation velocity as a function of the tube diameter according to the data of Peraldi et al. (1986).
NONIDEAL DETONATION WAVES IN ROUGH TUBES

From a comparison of Figs. 4 and 8, it follows that for tubes of small diameters \( r \approx 10^{-2} \text{ m} \) the limiting drag coefficients \( C_f \) in the two models (of the wall and bulk mixture ignition) coincide by an order of magnitude. However, the reaction zone in the wall-ignition model is much longer than in the bulk-ignition model. This means that the high-velocity detonation regime may be realized only in tubes with self-ignition low \( \lambda \). In tubes of large diameters \( C_f \) is high (this follows from the similarity condition \( C_f/r = \text{idem} \)). Therefore, the blockage ratio in such tubes may be high, yet the high-velocity detonation regime is still possible.

Near the limit of the high-velocity regime the detonation velocity is nonunique in the 1-D approximation. The data obtained by Lee et al. (1984) seem to confirm this nonuniqueness. When \( \lambda \) is below its limiting values for the high- and low-velocity regimes, which of the two regimes will be realized in practice is a priori unknown (provided that the 1-D approximation describes the real detonation wave more or less correctly).

Nonuniqueness of the Detonation Regimes in Rough Tubes

To illustrate the nonuniqueness of detonation processes in rough tubes, we considered a 1-D problem that includes the two possible ignition mechanisms. It is assumed that the core flow ahead of the flame front expands adiabatically due to the action of the reacting boundary layer. In such an approach one can use the results of the 1-D calculations of the reaction zone in a detonation wave with wall ignition up to the instant when the self-ignites in the core flow. As the detonation velocity increases, the self-ignition point in the core flow approximates the leading wave front and the bulk reaction becomes possible in addition to the reaction in the boundary layer.

The calculations of such a detonation wave were carried out for \( r = 10^{-2} \text{ m}, C_f = 0.05, C_h = 0.005, E/R = 18000 \text{ K}, m = 1, \) and \( \gamma = 1.3 \). The calculation results are presented in Fig. 13. Characteristic points in which one of the conditions [Eq. (11)] is met were indicated in the reaction zone for each fixed value of \( D \). Lines I and II represent loci in which \( D = \omega C \). Lines AB and GD are drawn through the points in which the condition in Eq. (11b) is met. Line III represents loci where self-ignition is observed in the adiabatic core flow. As seen from the graph, the conditions in Eqs. (11a) and (11b) are fulfilled simultaneously in two points, B and G. Point B corresponds to the low-velocity detonation with \( D \approx 0.72D_0 \). The reaction zone is long (\( \beta \approx 10r \)) and \( \beta \approx 0.1 \).

Point G pertains to the high-velocity detonation with \( D \approx 0.39D_0 \). The reaction zone is short, and the unburned fraction is small (\( \beta \approx 0.005 \)).

The preceding example clearly shows that the simplified 1-D approach to the detonation velocity calculations (with dissociation relaxation, and other factors being neglected) in rough tubes yields two detonation velocities in a certain region of parameters. The question of which of these
regimes is realized in reality can be answered after solving the nonsteady 2-D problem. Thus we can conclude that

1) The losses diminish the detonation velocity, change the structure of the reaction zone, and may result in the onset of multifront structures and nonunique selection of detonation velocity.

2) Detonation is not possible at every level of loss: there exist limiting values of the losses at which the eigenvalue problem of detonation velocity calculation has no solution.

3) An approximate scaling of the process is possible based on the 1-D solution.

Experimental

To check the stability of detonations in rough tubes and the feasibility of the two previously mentioned detonation regimes, we have conducted experimental studies in a detonation tube. Two versions of the tube were used. In the first version, detonation was initiated by exploding a small volume of the stoichiometric propane-oxygen mixture in a smooth tube (70 mm in diam and 9 m long); then the mixture entered a flexible metal hose of 68-mm i.d. and 3.1-m long. The corrugations (obstacles) were 6-mm high and spaced 6 mm apart. Beyond the hose, the detonation wave again entered a
smooth tube of the same diameter and was monitored along 11 m of the tube. Both the average wave velocity and its distribution along the hose were measured. In the second version, detonation was initiated in a smooth tube 70 mm in diam and 28-m long; it then entered a flexible metal hose 18-m long. The detonation velocity was measured at several bases along the hose. Experiments were carried out with propane-air, hydrogen-oxygen-nitrogen, and methane-air mixtures. Each mixture was prepared at an elevated pressure in a mixer and then an amount of about three tube volumes was channeled thru the tube.

Figure 14 shows the detonation velocity in the smooth tube and the mean wave velocity in the 3.1-m-hose as functions of the fuel (propane) concentration in air. As with other mixtures, the mean detonation velocities in the hose are much lower than in the smooth tube. From this it follows that a detonation wave entering the rough tube rapidly changes structure and propagates at a unique mean velocity corresponding in the case under consideration to the wall-ignition regime.

Two more peculiarities of the above data are worth noting. After the detonation wave passes by the rough tube section, it recovers almost immediately in the smooth tube but within a narrower concentration range than the detonation limits in a smooth tube. The detonation wave in the smooth tube after it escapes the rough section has a velocity that is higher than the CJ velocity. This is an indication of the fact that transition from the wall-ignition

![Graph showing detonation velocity as a function of propane concentration](image-url)

Fig. 14 Detonation velocity in the 3.1-m-long metal hose and in the smooth tube for propane-air mixtures as a function of the mixture composition. Curve 1 is for the smooth tube and curve 2 for the rough one. Vertical dashed lines show the limits of detonation recovery in the smooth tube.
regime to the normal detonation occurs via "explosion in explosion" and overdriven detonation.

The second peculiarity is that the limits of low-velocity detonation are somewhat narrower than those in a smooth tube and that the detonation velocity at the limit in a rough tube drops down to very low values \( M \approx 2 \). This is illustrated by a comparison of curves 1 and 2 in Fig. 14. The extreme points for the rough tube pertain to the low-velocity detonation limits, and the vertical dashed lines indicate the limiting mixture compositions at which the low-velocity detonation recovers in the smooth tube.

Lee et al. (1984) and Peraldi et al. (1986) report the data that give evidence of the nonuniqueness of the detonation velocity in rough tubes in hydrogen-air mixtures. However, our data (Zeldovich et al. 1984) seem to indicate that detonation propagates with a single velocity. A question arises in this regard: How stable is the low-velocity detonation (i.e., will it propagate at the same velocity for longer distances)? It was also interesting to note how the low-velocity detonation converts into the normal CJ detonation when the mixture reactivity is increased. Such a transition was studied in this work using hydrogen-oxygen-nitrogen mixtures of different compositions. The measurements of the mean wave velocity in the 0.31-m-long hose demonstrate that each mixture has its own detonation velocity. A comparison of curves 1 and 2 obtained in the smooth and rough tubes (Fig. 15) shows that the transition from one detonation regime to the other occurs smoothly (though there

![Fig. 15 Detonation velocity in the smooth (1) and rough (2) tube as a function of the composition of the H₂-O₂-N₂ mixture. The data are obtained in the 3.1-m-long hose.](image-url)
exists a steep portion of the D-nitrogen content curve. The velocity deficit comes close to deficits characteristic of the bulk self-ignition mechanism when the oxygen concentration exceeds 25%. In real detonation waves that are to be described by multidimensional models, the heat may be released by a mixed mechanism, and the velocity deficit may acquire intermediate values between the two extreme cases mentioned previously. It should be emphasized here that the detonation wave "feels" the losses at the rough tube walls, even when the reaction zone is short (notice the difference between curves 1 and 2 in Fig. 15). There is no well-defined criterion for determining the conditions at which the detonation wave ceases to feel the wall roughness, and therefore the concept of "three detonation cells" proposed by Feraldi et al. (1986) is somewhat conventional.

Since the wave velocity dropped to very low values in the 3.1-m-long hose (Fig. 16), a question arose whether the low-velocity detonation was capable of further steady propagation. Indeed, for the incident waves propagating at velocities of 600-700 m/s in propane-air mixtures, the ignition delays even in reflected shock waves must be much above the millisecond range; hence such a shock wave is not likely to be capable of driving a steady detonation process.

The experiments with the 15-m hose section were conducted to answer this question. The detonation velocities as measured with pressure transducers along the hose are plotted in Fig. 16. A characteristic feature of the data shown in this figure is a deep minimum on the D-distance curve near the point of wave entry into the hose. This

Fig. 16 Detonation velocity in the rough tube as a function of the distance from the hose front edge for the propane-air mixture.
indicates that the low wave velocities (600-700 m/s) are not characteristic of the steady detonation regime. The wave accelerates after the first 3 m of its travel in the hose and reaches a mean velocity of about 900-950 m/s. However, it should be noted that the scatter of the measured detonation velocities from run to run and in a single run is rather high. Jumpwise velocity fluctuations that attain 200 m/s are observed. This is evidence of the instability of the heat release zone behind the lead shock front, associated presumably with the strong turbulization of the flow, local combustion quenching, and self-ignition of a part of the mixture in the volume.

Smoked plates positioned radially along the rough tube gave rather inconclusive information about the wave structure. However, the smoked plate writings reveal some interesting features of the process. For instance, the flow near the obstacles has no structure characteristic of an over-driven detonation. This indicates that only "mild" ignition occurs, evidently in the space between the obstacles, without formation of detonation waves. Inasmuch as detonation waves in rough tubes have very low velocity, which is insufficient for the ignition delays to be short enough (10^{-4} s and lower), even in reflected waves the ignition near the obstacles can be expected to occur in very small volumes owing to focusing of the shock waves. This explains the detonation propagation at unreasonably low velocities.

Furthermore, inside the tube the smoke line from those characteristic of a turbulent flame, since against the structureless background there appear some sporadic prints that furnish evidence of a formation of local waves with a cellular structure.

Hence, from the experimental studies of detonation in rough tubes, it follows that certain phenomena exist that require for their explanation a non-1-D model, although the 1-D model gives a qualitatively correct description of the effect of losses on the velocity and structure of the wave. Among these phenomena are (1) the cellular wave structure observed in experiments, where the detonation velocity is much lower than that inherent in the waves with bulk ignition of the mixture; and (2) the strong large-scale instability of the low-velocity detonation regimes. The fact that detonation velocity goes through a minimum when the wave travels from the smooth tube to the rough one also merits special consideration.

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