

PULSE-DETONATION STEAM SUPERHEATER

**S. M. Frolov^{1,2}, V. A. Smetanyuk^{1,2}, I. O. Shamshin^{1,2},
and F. S. Frolov¹**

¹N. N. Semenov Federal Research Center for Chemical Physics
of the Russian Academy of Sciences
Moscow, Russian Federation

²Federal State Institution “Scientific Research Institute
for System Analysis of the Russian Academy of Sciences”
Moscow, Russian Federation

Systematic experiments to determine the concentration limits of detonation of ternary propane/methane–oxygen–steam mixtures under normal atmospheric pressure have been conducted. The experiments are performed in an innovative pulse-detonation steam superheater (PDSSH) with cyclic detonations of ternary mixtures at variation of fuel-to-oxygen equivalence ratio (from 0.14 to 1.77 in propane mixtures and from 0.3 to 1.84 in methane mixtures) and steam volume fraction (from 0 to 0.7). Experiments are supplemented by thermodynamic calculations. Cyclic detonations of ternary propane/methane–oxygen–steam mixtures allow the generation of highly superheated steam (HSS) with a temperature exceeding 2250 K at atmospheric pressure. The detonation products of stoichiometric ternary mixtures under consideration can contain up to 80% HSS and up to 17% CO₂ as well as CO, O₂ and H₂ in trace amounts. It is proposed to use such a high-temperature environment for deep processing (gasification) of organic municipal and industrial wastes to produce a gas mixture of CO and H₂ which can be further used as a fuel gas for PDSSH operation, heat/electricity production, and as a raw material for methanol and synthetic motor fuel production. Due to periodic filling of the PDSSH with the cool ternary gas mixture, the temperature of PDSSH walls and inner elements increases insignificantly, so that conventional (not heat-resistant) construction materials can be used for its production.

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1 Introduction

At present, the problem of ecologically clean processing and utilization of municipal and industrial wastes is one of urgent problems of modern society. Thermal treatment of wastes is currently considered as the most effective solution to this problem due to relatively low environmental impact as well as the possibility of partially recovering energy and material resources. The corresponding technologies are based on physicochemical processes including deflagration (combustion), detonation, pyrolysis, and gasification. Deflagration is the transformation of the matter due to overall exothermic self-accelerating chemical reactions, like oxidation reactions, induced by molecular and turbulent transport of energy and reactants. Detonation is the transformation of the matter due to overall exothermic self-accelerating chemical reactions induced by a strong self-sustaining shock wave due to volumetric compression and heating. Pyrolysis and gasification usually imply the overall endothermic processes of thermal degradation of the matter in the absence and in the presence of a gasifying agent, respectively.

Combustion of wastes in air results in the formation of harmful gaseous pollutants, like NO_x, SO_x, dioxins, furans, etc., as well as fly ash and ashes [1–4]. Detonation is primarily used for disposal of hazardous wastes like explosives and highly reactive materials (nitrocompounds, organic peroxides, etc. [5]). Pyrolysis and gasification of wastes can potentially reduce the production of the various pollutants due to the absence or reduced amount of oxygen. However, for providing the required heat for pyrolysis and gasification, the existing technologies usually use combustion processes or apply air as a gasifying agent [6, 7]. The other substances applied as gasifying agents are nitrogen, carbon dioxide, and steam [8–10]. Pyrolysis and gasification are implemented at temperatures ranging from 900 to 1300 K at most and result in production of gases like light hydrocarbons, tarry products, CO₂, H₂, CO, and solid residues (pyrocarbon) [11–13]. The technologies based on gasification of solids and liquids (coal, lignin, biomass, plastics, crude oil, etc.), especially with steam as a gasifying agent, are widely used for production of hydrogen, syngas, olefins, etc. [14–18]. The conversion efficiency and the yields of end gases are known to drastically increase with the pyrolysis/gasification temper-

ature, whereas the yield of harmful substances is known to drastically decrease in these conditions. The gasification of wastes with supercritical water (at temperature $T > 647$ K and pressure $P > 22.1$ MPa), despite many potential advantages, requires extremely high operation pressures which makes the technology costly [19]. Thus, there is obviously a need in the technologies based on pyrolysis and gasification of wastes in a steam-containing environment with temperatures well exceeding 1300 K and near-atmospheric pressures. Processing of organic municipal and industrial wastes in such a high-temperature environment will be accompanied by their complete gasification and thermal decomposition to the simplest molecules like H_2 and CO composing a syngas which could be further used for production of synthetic natural gas, methanol, diesel, or di-methyl ether. The target value of the H_2/CO ratio is possible to adjust [20, 21]. Also, the resultant syngas can be used as a fuel gas for producing heat and/or electricity. The sulfur and chlorine containing wastes will be transformed to the corresponding liquid acids (after condensation [22]), while solid inorganic materials will be transformed to the molten slag consisting of simple oxides and salts, an excellent environmentally friendly construction material.

One of the known technological solutions in this respect is based on using the HSS (with a temperature above 2000 K) obtained by burning hydrogen–oxygen mixture [23]. Another solution is to use a mixture of syngas, consisting of CO and H_2 , with steam preheated to the abovementioned temperature [24]. Practical implementation of such technologies is believed to provide economically efficient processing of wastes of any morphological and chemical composition with full utilization of material and energy resources contained in wastes without any harmful emissions into the atmosphere and water bodies. Unfortunately, due to problems with thermal insulation of combustion devices and reactors, these technologies have not yet been implemented even in the form of pilot plants.

In [25–27], we proposed a new method and devices for obtaining HSS with temperatures exceeding 2000 K at atmospheric pressure, in which the problems of thermal insulation of combustion devices and reactors are solved by substitution of conventional deflagration by detonation and transition from steady-state to cyclic operation process. Highly superheated steam is proposed to be obtained in a PDSSH

by means of cyclic detonations of ternary fuel gas–oxidizer–steam mixture. (The fundamentals of gaseous and spray detonations and the operation principles of pulse-detonation devices are comprehensively reviewed in [28]). Hydrogen, syngas, natural gas, propane, etc. can be used as a fuel gas, while oxygen, air enriched with oxygen, or pure air can be used as an oxidizer. In [25], the variants of obtaining HSS in PDSSH are considered. One variant uses a premixed fuel gas–oxidizer–steam mixture, the composition of which is within the concentration limits of detonation, and HSS is obtained because of compression and heating of the initial steam in propagating detonation waves (DWs). In the other variant, HSS is obtained through compression and heating of steam by propagating shock waves generated by detonation of a fuel gas–oxidizer mixture. In both variants, HSS is additionally obtained as a product of detonation of fuel gas. With the help of devices proposed in [25–27], there is a possibility of practical implementation of technologies [23, 24]: the walls and internal elements of PDSSH are heated to relatively low temperature (up to ~ 800 K [29]) due to periodic filling of cool ternary gas mixture, i. e., steam superheater can be made of conventional (not heat-resistant) construction materials.

It is worth noting that the literature contains many publications on the effect of steam on deflagration properties (see, e. g., [30–32]) but only few publications on the effect of steam on the properties of gaseous detonations and shock-induced ignition. The latter deal mainly with hydrogenous mixtures [30, 33–39] as well as with mixtures of carbon monoxide [30] and H_2/CO blends [40] and are mostly related to explosion safety of nuclear reactors rather than to production of HSS. Reported in [34, 35, 38] are the results of measurements of the detonation cell size in hydrogen–air–steam mixtures. The cell width is shown to increase with the steam concentration in the mixture. Addition of steam to the mixture significantly narrows its range of detonability in terms of hydrogen concentration. Detonation in the stoichiometric ternary hydrogen–air–steam mixture is possible at steam volume fraction less than about 40% [38]. The ignition delay times of hydrogen–air–steam mixtures measured in a heated shock tube behind reflected shock waves show a strong dependence on steam concentration and weak influence of pressure [39]. According to theoretical analyses in [40], addition of CO to H_2 –air mixtures

can increase their detonation sensitivity. Thus, 10% H₂–air mixture becomes detonable when 5% CO is added. Addition of steam to H₂–CO–air mixtures reduces their detonation sensitivity.

The objective of this work is to determine the quantitative characteristics (velocity, detonability limits, etc.) of propagating detonations and detonation products (temperature, composition, volume fraction of HSS, etc.) of premixed ternary propane–oxygen–steam and methane–oxygen–steam mixtures at normal atmospheric pressure. It is implied that propane and methane (natural gas) could be used as starting fuels for PDSSH with further replacement by syngas generated during municipal and industrial wastes gasification in the HSS environment.

2 Experimental Setup

Investigations are performed on a specially designed and fabricated experimental setup (Fig. 1). The main elements of the setup are the PDSSH, the system for supplying combustible mixture components (fuel gas and oxidizer), the system for heating and supplying low-temperature (slightly above 373 K) steam to PDSSH, the measuring system, and the control system. Propane and methane are used as fuel gases. Technical oxygen is used as an oxidizer.

The PDSSH is a 50-millimeter diameter, 2.7-meter long round tube with one open and one closed ends, made of steel. The open end of the PDSSH is connected to an acoustic absorber communicating with the atmosphere. The closed end of the PDSSH is equipped with the ports for cyclic separate supply of fuel gas and oxygen through lines with electromagnetic solenoid valves (EMV). Two ignition sources (standard automotive spark plugs) are mounted downstream from the ports. The supply of fuel gas to PDSSH is controlled by one EMV, whereas the supply of oxygen is controlled by four EMVs. The power consumption and supply voltage of EMVs are 27 W and 24 V, respectively. For reliable cyclic initiation of detonation, a 1.5-meter long Shchelkin spiral (see [28]) made of steel wire with a diameter of 6 mm and a pitch of 50 mm is inserted into the PDSSH. The sections of PDSSH with Shchelkin spiral are equipped with cooling jackets and cooled with water (see Fig. 1*a*).

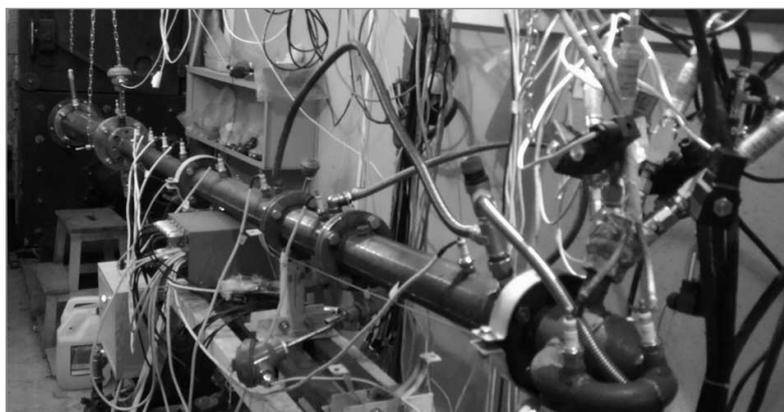
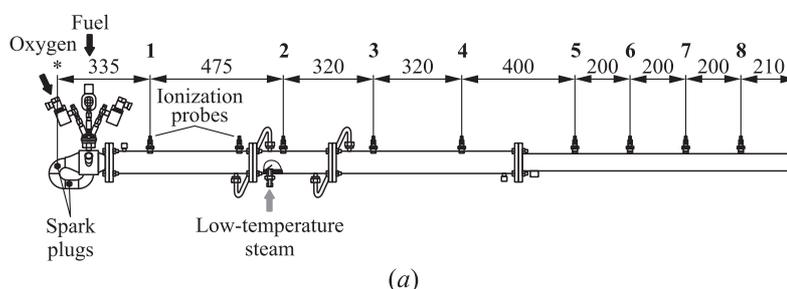


Figure 1 Schematic (a) and photograph (b) of the experimental setup. Dimensions are in millimeters

The fuel gas is delivered to the PDSSH from a 25-liter receiver. Before the beginning of experiment, the receiver is filled with a fuel gas to a pressure of 0.3–0.4 MPa (propane) or 0.8–1.0 MPa (methane). The supply pressure of fuel gas is controlled by a reducer (BPO-5-3) and ranges from 0.02 to 0.12 MPa for propane and from 0.02 to 0.32 MPa for methane. Oxygen is delivered to the PDSSH from a 40-liter high-pressure receiver (up to 6.0 MPa). The pressure of oxygen supply to the PDSSH is controlled by a reducer (BKO-50) and ranges from 0.09 to 0.2 MPa.

The source of low-temperature steam delivered to the PDSSH is a boiler with electric heaters of adjustable capacity, filled with water. During the experiment, steam is delivered from the boiler to the PDSSH through a thermally insulated line under a small overpressure (about 8 kPa) with a temperature of 375 K downstream from the ignition sources (shown by the arrow in Fig. 1a). The steam flow rate is controlled by the capacity of electric heaters. A special guiding device ensures that steam is supplied only toward the open end of the PDSSH. This ensures reliable initiation of a detonation in a fuel gas–oxygen mixture at a short distance from the ignition sources and subsequent transmission of the detonation to a ternary fuel gas–oxygen–steam mixture in a wide range of compositions. The feed system of ternary mixtures is set up so that the PDSSH is filled with the mixture completely. The mass flow rates of mixture components are varied within the following ranges: propane (0.05–0.5 g/s), oxygen (0.2–2.0 g/s), and steam (0–1.5 g/s) in propane mixtures, and methane (0.2–1.6 g/s), oxygen (1.2–6.3 g/s), and steam (0–5.1 g/s) in methane mixtures, so that the fuel-to-oxygen equivalence ratio (ER) is varied from 0.14 to 1.77 in propane mixtures and 0.3 to 1.84 in methane mixtures. The volume fraction of steam injected into the combustible mixture, X , is varied between 0 and 0.7.

The propagation velocity of reaction fronts including DWs is measured by a set of eight ionization probes (IPs) using the methodology described in detail in [41]. Ionization probes are installed along the PDSSH as shown in Fig. 1a: IPs 1 to 4 are installed in the section of PDSSH with Shchelkin spiral, whereas IPs 5 to 8 are installed in the section of PDSSH without spiral. The reaction front velocity is determined by the distance between the IPs (measuring segments) and the time taken for the reaction front to travel between them. The error of reaction front velocity measurement is 100 m/s ($\sim 5\%$ at the velocity on the level of 2000 m/s). Note that the measurements of the reaction front velocity by IPs proved to be well consistent with measurements based on high-frequency pressure sensors (PCB 113B24) installed in the same measuring ports 5 to 8 in the experiments with successful detonation initiation. However, in most of the experiments discussed herein, expensive pressure sensors were not used due to the risk of their failure during long-term operation within the PDSSH.

The temperature of the PDSSH wall is controlled by a K-type thermocouple with an error of 1%. The temperature of steam supplied to the PDSSH is measured by the thermoresistor (TSP Pt100 type) with an error of 0.5%. The average mass flow rates of fuel gas and oxygen are determined by the pressure drop in the fuel gas and oxygen receivers at the end of the experiment after the temperature of the receivers increases to the ambient temperature. The error in determining the average fuel-to-oxygen equivalence ratio of a combustible mixture is estimated as 15%. The average mass flow rate of steam is determined based on the change in the weight of the boiler during experiment. In preliminary experiments, the dependence of the boiler weight change on the power of electric heaters is obtained. The error of measurement of the steam mass flow rate is estimated as 10%.

The experiment is fully controlled by the automatic control system. At first, the PDSSH operates in the frequency mode without supply of low-temperature steam, so that the PDSSH walls are heated to a temperature of about 380 K. Thereafter, low-temperature steam is supplied to the PDSSH together with fuel gas and oxygen. From that moment on, cycles with initiation of detonation and its propagation through the ternary mixture are counted. Each experiment includes from 20 to 40 cycles with a pulse frequency of 0.2 Hz. The low frequency is associated with relatively low mass flow rates of steam in the experiments, which imposed limitations on the mass flow rates of fuel gas and oxygen.

3 Results and Discussion

Figure 2 shows examples of primary records of IPs for the propagation of DWs in the PDSSH filled with the binary propane–oxygen mixture (Fig. 2a) and the ternary mixture diluted with steam (Fig. 2b). In the ternary mixture, the DW propagates with a lower velocity due to dilution of the mixture by steam: the same distance from the first IP (# 1 in Fig. 2) to the last IP (# 8) takes longer time (1 ms instead of 0.82 ms).

In Fig. 3, solid curves with symbols show examples of changes in the reaction front propagation velocity with the distance traveled during the transmission of DWs from the binary fuel gas–oxygen mixture

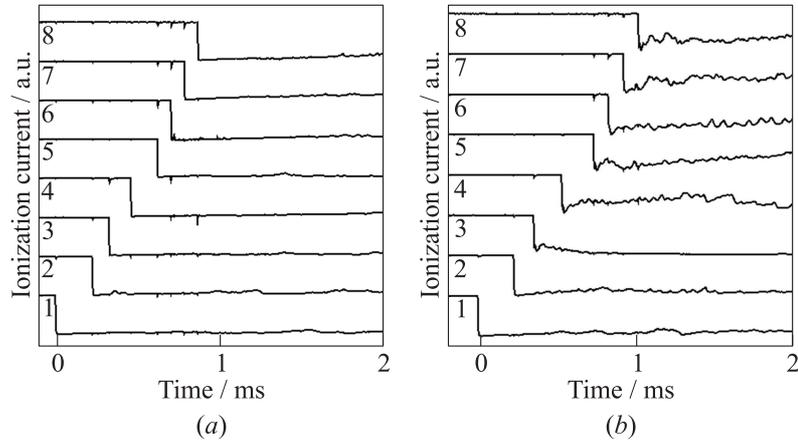


Figure 2 Primary records of eight (1 to 8) IPs at detonation propagation in binary propane–oxygen mixture ($X = 0$) (a) and ternary mixture with steam ($X = 0.58$) dilution (b)

to the ternary fuel gas–oxygen–steam mixture at different values of ER and X . From now on, each figure contains the results for propane and methane separately. Different symbols correspond to different cycles in the PDSSH operation. Horizontal dashed lines correspond to the thermodynamic Chapman–Jouguet (CJ) detonation velocity D_{CJ} in the ternary mixture predicted by the CANTERA code [42]. In all the examples, a dip in the reaction front velocity is first observed, with the depth and width of the dip increasing with the steam volume fraction in the ternary mixture. After the dip, the reaction front velocity increases and attains a level close to D_{CJ} . In Figs. 3a and 3d, there is a small (3%–4%) deficit in the detonation velocity as compared with D_{CJ} , which is explained by momentum and energy losses [43]. In Figs. 3b and 3e, the deficit is getting somewhat indefinite due to enhanced fluctuations in the velocity of propagating detonations. In general, the examples in Figs. 3a, 3b, 3d, and 3e demonstrate good cycle-to-cycle reproducibility of the results with achieving a self-sustaining detonation at the last three measuring segments (5–6, 6–7, and 7–8) of the PDSSH. The corresponding mode of the reaction front propagation is treated by us as the normal detonation mode.

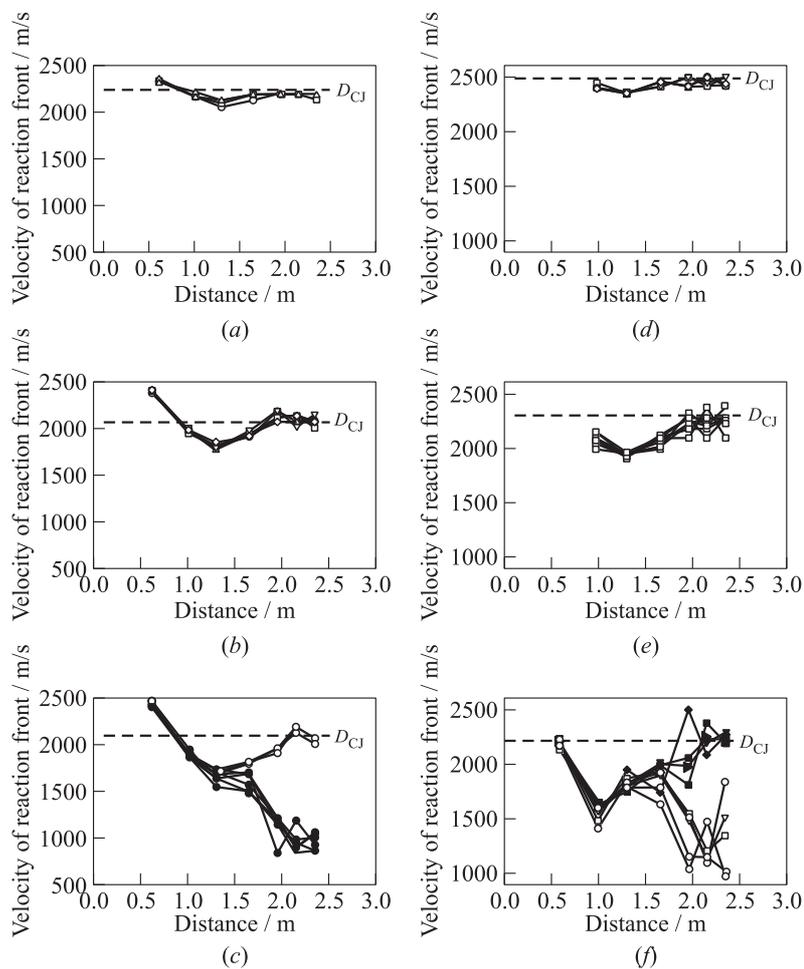


Figure 3 Dynamics of detonation transmission from the binary fuel gas – oxygen to ternary fuel gas – oxygen – steam mixture at different values of ER and X : (a) ER = 1.0, X = 0.3; (b) ER = 1.04, X = 0.58; (c) ER = 1.17, X = 0.62; (d) ER = 1.22, X = 0.0; (e) ER = 1.19, X = 0.33; (f) ER = 1.08, X = 0.42; left column — propane; and right column — methane

The examples shown in Figs. 3*c* and 3*f* correspond to the case when cyclic instability is observed: in some random cycles, there is a dip in the reaction front propagation velocity with the subsequent recovery of the detonation and its propagation in the overdriven mode, and in others, there is a progressive reduction of the propagation velocity, i. e., detonation decay. This mode of reaction front propagation is interpreted by us as the limiting detonation mode, i. e., corresponding to the concentration limit of detonation in terms of steam content. In addition to the normal and limiting modes of detonation, the experiments register a trivial mode with detonation decay, in which a progressive decrease in the propagation velocity of the reaction front is registered from cycle to cycle.

Figure 4 shows the dependences of the DW propagation velocity on different steam contents in the ternary mixtures ($X = 0, 0.3, 0.4, 0.5,$ and 0.6 for propane mixtures and $X = 0; 0.2; 0.3;$ and 0.4 for methane mixtures). From now on, the DW velocities are obtained by averaging the values measured at the last three measuring segments 5–6, 6–7, and 7–8 of the PDSSH. For the sake of comparison, the results of thermodynamic calculations are shown by curves. The measured values of detonation velocity are seen to be generally in reasonable agreement with the thermodynamic calculations.

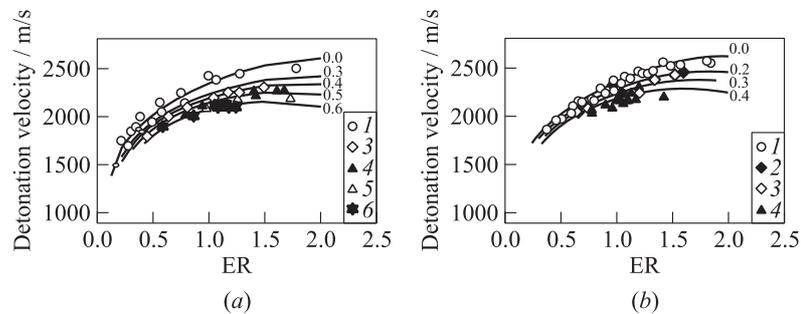


Figure 4 Detonation propagation velocity as a function of ER for ternary propane (a) and methane (b) mixtures with different steam dilution: curves correspond to thermodynamic calculations and symbols correspond to measurements at different values of ER and X : 1 — $X = 0.0$; 2 — 0.2 ; 3 — 0.3 ; 4 — 0.4 ; 5 — 0.5 ; and 6 — 0.6

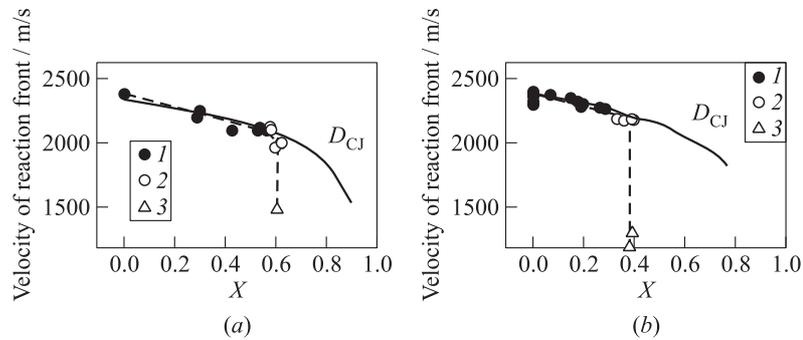


Figure 5 Detonation propagation velocity in the ternary stoichiometric propane (a) and methane (b) mixtures diluted with steam as a function of steam volume fraction: solid curves correspond to the thermodynamic calculation ($ER = 1$), symbols correspond to measurements at $ER = 0.9$ – 1.1 for propane and $ER = 0.8$ – 1.2 for methane (1 — normal detonation mode; and 2 — limiting detonation mode); 3 — detonation decay; and dashed curves approximate measurements

Figure 5 shows the dependences of the measured and thermodynamic DW velocity on the steam volume fraction in the ternary propane and methane mixtures with composition close to stoichiometric ($ER \approx 1$). In the PDSSH under consideration, the limiting volumetric content of steam in the ternary mixture (concentration limit of detonation in terms of steam content), X_{lim} , is about 0.6 for propane and 0.4 for methane. When the steam volume fraction in the triple mixture increases above X_{lim} , the self-sustaining detonation becomes impossible. It should be noted that the thermodynamic calculation does not include the momentum and energy losses from the reaction zone [43]; so, the predicted concentration limit of detonation tends to occur at $X_{lim} \rightarrow 1$.

Figure 6 shows the parametric domains of existence of cyclic detonations in the ternary propane and methane mixtures on the X – ER plane. The curves separating the region “detonation go” from the region “detonation no go” are drawn between experimental points corresponding to the normal and limiting detonation modes. In some cases, the limiting detonation mode is not detected in the experiment:

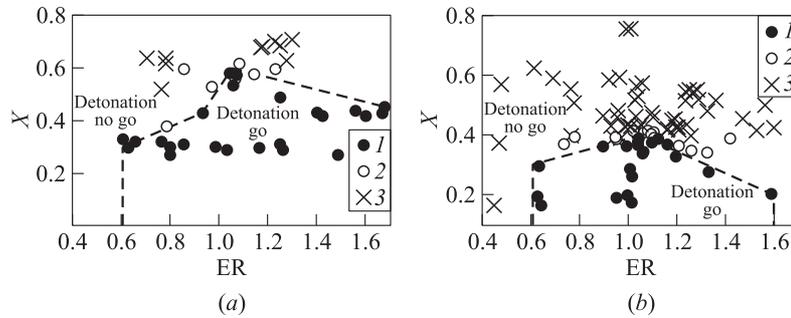


Figure 6 Domains of detonation existence for the ternary propane (a) and methane (a) mixtures on the X - ER parametric plane: 1 — normal detonation mode; 2 — limiting detonation mode; and 3 — detonation decay

with a small change in X or ER , there is a transition from the normal detonation mode to the mode with detonation decay. In these cases, the curves in Fig. 6 are drawn between the points corresponding to the normal detonation mode and the mode with detonation decay. It follows from Fig. 6a that the maximum steam content (60%), at which detonation of the ternary propane mixture is still possible, is achieved at $ER \approx 1.05$. Detonation of fuel-rich propane mixtures with $ER > 1$ looks considerably less sensitive to steam dilution than detonation of fuel-lean propane mixtures with $ER < 1$. Thus, the detonation limit of fuel-lean propane mixtures with $ER = 0.4$ – 0.8 is reached with the addition of 30%–35% steam, whereas the detonation limit of fuel-rich mixtures with $ER = 1.2$ – 1.7 is attained with the addition of 45%–50% steam. As for the ternary methane mixtures, the maximum steam content (40%), at which cyclic detonations are still possible, is also achieved at $ER \approx 1.05$. Contrary to the ternary propane mixtures, detonation of fuel-rich ternary methane mixtures with $ER > 1$ looks somewhat more sensitive to steam dilution than detonation of fuel-lean ternary methane mixtures with $ER < 1$. It is important to note that for the ternary mixtures of both fuel gases, the measured wall temperature of PDSSH in the current experiments does not exceed 400 K.

Reasonable agreement between the measured and calculated values of the detonation velocity obtained in Figs. 4 and 5 suggests that the thermodynamic calculations correctly estimate the temperature and composition of detonation products obtained in the experiment. Figure 7 presents the results of thermodynamic calculations of temperature, T_{CJ} (Figs. 7a and 7b), and composition (Fig. 7c and 7d) of detonation products (at the CJ point) of ternary propane and methane mixtures depending on ER and X . Shaded areas indicate the conditions in which the normal detonation mode has been experimentally registered. One can see that the minimal temperature of detonation products exceeds 2900 K for ternary propane mix-

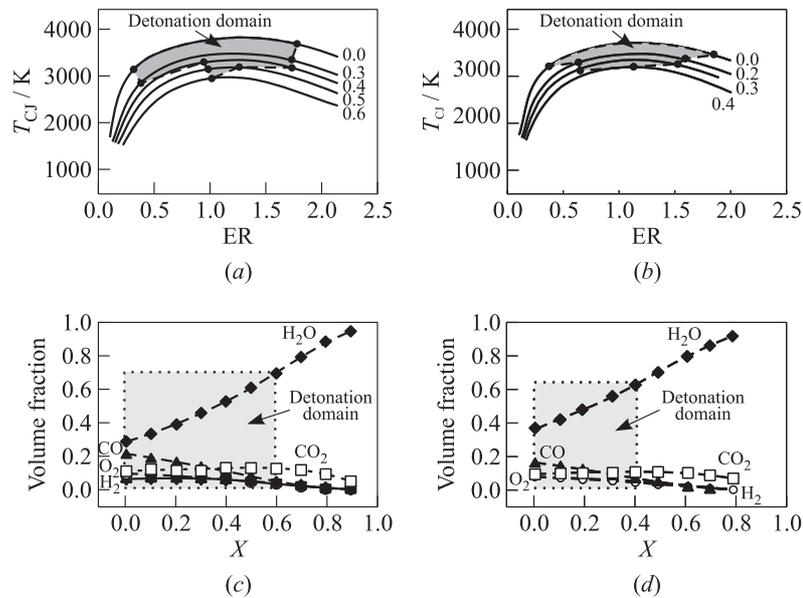


Figure 7 Temperature and composition of detonation products of ternary propane (left column) and methane (right column) mixtures in the CJ plane at different values of ER and X . Curves correspond to the thermodynamic calculations. Shaded areas indicate conditions in which the normal detonation mode is experimentally registered

tures (see Fig. 7a) and 3200 K for ternary methane mixtures (see Fig. 7b). The maximum volume fraction of steam in the detonation products of the ternary stoichiometric propane mixture reaches 70% (at $X = X_{\text{lim}} = 0.6$, see Fig. 7c). In addition to steam, the detonation products of such a mixture mainly contain CO_2 (up to 12%), CO (up to 5%), O_2 (up to 3%), and H_2 (up to 4%). As for the ternary stoichiometric methane mixtures, the maximum volume fraction of steam in its detonation products reaches 63% but at $X_{\text{lim}} = 0.4$, while the volume fractions of CO_2 , CO , O_2 , and H_2 attain nearly the same values as in the ternary propane mixture (see Fig. 7d).

The pressure in DWs is much higher than the atmospheric pressure. According to the thermodynamic calculations (Fig. 8), the pressure at the CJ point, P_{CJ} , under experimental conditions varies from about 1.3 to 3.2 MPa for ternary propane mixtures (Fig. 8a) and from about 2.0 to 3.1 MPa for ternary methane mixtures (Fig. 8b). When the detonation products expand to 0.1 MPa (i. e., when the DW exits from the PDSSH to the atmosphere or to a waste-gasification reactor), their temperature decreases. To determine the temperature of the detonation products after expansion, we have performed additional thermodynamic calculations.

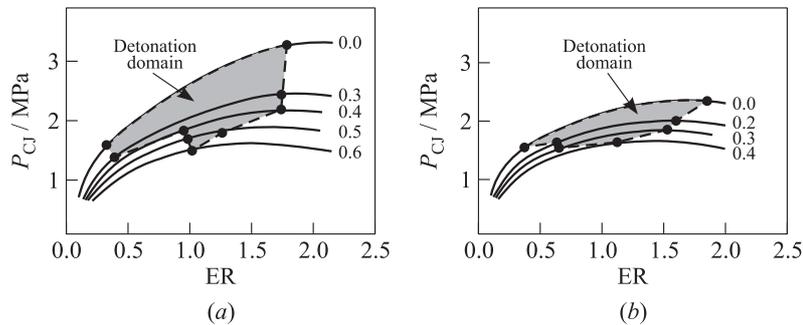


Figure 8 Pressure of detonation products of ternary propane (a) and methane (b) mixtures in the CJ plane at different values of ER and X . Curves correspond to the thermodynamic calculations. Shaded areas indicate conditions in which the normal detonation mode is experimentally registered

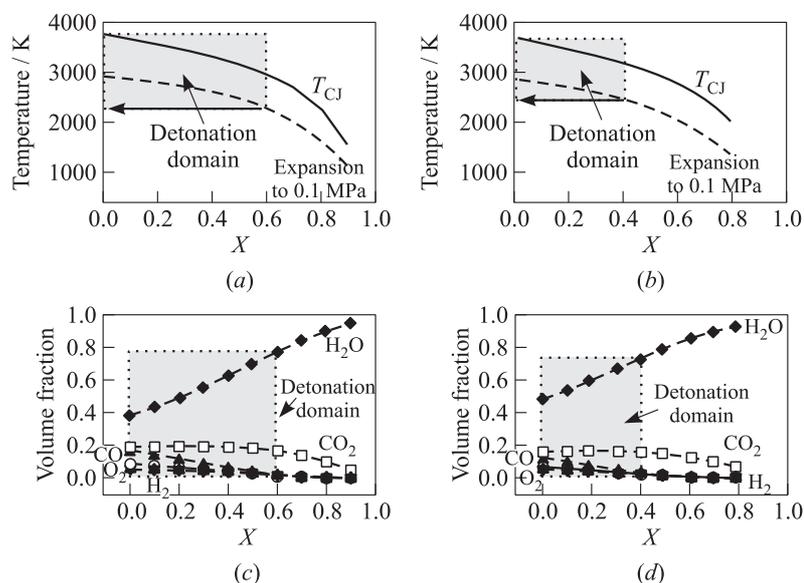


Figure 9 Temperature and composition of detonation products of ternary stoichiometric propane (left column) and methane (right column) mixtures as functions of steam volume fraction X after isentropic expansion to 0.1 MPa: shaded areas indicate conditions in which the normal detonation mode is experimentally registered

Figure 9 shows the predicted temperature and composition of isentropically expanded detonation products as functions of steam volume fraction X in the stoichiometric ternary propane (Fig. 9a) and methane (Fig. 9b) mixtures. Again, the shaded areas indicate the conditions in which the normal detonation is experimentally registered. An important conclusion follows from Fig. 9: within the concentration limits of detonation, the temperature of expanded detonation products of the stoichiometric ternary propane and methane mixtures exceeds 2250 and 2500 K, respectively. In these conditions, the detonation products of the ternary propane mixture contain mainly HSS (about 80%) and CO_2 (about 18%), whereas the detonation products of the ternary methane mixture contain mainly HSS (about 75%) and CO_2 (about 15%) (see Figs. 9c and 9d).

4 Concluding Remarks

Systematic experiments to determine the concentration limits of detonation of ternary propane–oxygen–steam and methane–oxygen–steam mixtures under normal atmospheric pressure are conducted. The experiments are performed in the PDSSH with multiple cyclic detonations of the ternary mixtures at variation of ER from 0.14 to 1.77 in propane mixtures and from 0.3 to 1.84 in methane mixtures, and steam volume fraction X from 0 to 0.7. The experiments are supplemented with thermodynamic calculations for estimating the temperature and composition of detonation products. The following results are obtained:

- three modes of reaction front propagation are experimentally registered: normal detonation mode, limiting detonation mode, and detonation decay;
- the parametric domains of detonation existence on the ER– X plane are determined experimentally for the ternary mixtures of both fuels. The maximum steam content (60%), at which a detonation of a ternary propane mixture is still possible, is achieved at $ER \approx 1.05$. For the ternary propane mixtures, the detonation of fuel-rich mixtures with $ER > 1$ appears to be considerably less sensitive to steam dilution than the detonation of fuel-lean mixtures with $ER < 1$. As for the ternary methane mixtures, the maximum steam content (40%), at which a ternary mixture detonation is still possible, is also achieved at $ER \approx 1.05$. Contrary to the ternary propane mixtures, detonation of fuel-rich methane mixtures with $ER > 1$ appears to be somewhat more sensitive to steam dilution than detonation of fuel-lean methane mixtures with $ER < 1$;
- the measured values of the detonation velocity are generally in reasonable agreement with thermodynamic calculations;
- in the normal detonation mode, the calculated minimal temperatures of detonation products of ternary mixtures in the CJ plane exceed 2900 K for propane mixtures and 3200 K for methane mixtures. The calculated volume fractions of steam,

CO₂, CO, O₂, and H₂ in the detonation products of the stoichiometric ternary mixtures at the limiting X_{lim} values are about 70%, 16%, 5%, and 4% for propane and 60%, 12%, 5%, and 4% for methane mixtures, respectively;

- isentropic expansion of detonation products of the stoichiometric ternary propane–oxygen–steam and methane–oxygen–steam mixtures with the limiting X_{lim} values (0.6 and 0.4, respectively) to the atmospheric pressure leads to their temperature decrease to 2250 and 2500 K, respectively, and to increase in the maximum content of HSS to about 80% and 75%, respectively;
- the measured temperature of PDSSH walls in the experiment does not exceed 400 K. Despite this temperature increases with the operation frequency, it will remain relatively low due to periodic filling of the PDSSH with the cool ternary gas mixture; and
- it is expected that due to the known dependence of detonability limits on the detonation tube diameter (the less the diameter, the narrower the concentration limits), a PDSSH with a larger detonation tube will exhibit wider detonability limits in terms of ER and X_{lim} . The results obtained herein provide the grounds for further scalability studies required for designing a practical PDSSH.

Thus, cyclic detonations of ternary propane–oxygen–steam and methane–oxygen–steam mixtures allow one to obtain HSS with temperatures above 2250 K at atmospheric pressure. The volumetric content of HSS in the expanded detonation products can attain 75%–80% with the rest mostly represented by CO₂. Processing of organic municipal and industrial wastes in such a high-temperature environment is accompanied by their pyrolysis, thermal decomposition, and complete gasification (including pyrocarbon). As a result, a gas mixture of CO and H₂ (syngas) is generated which can then be used as a fuel gas for the PDSSH, for heat/electricity production, and as a raw material for methanol and synthetic motor fuels. The sulfur and chlorine containing wastes will be transformed to the corresponding liquid acids (after condensation), while solid inorganic materials

will be transformed to the molten slag consisting of simple oxides and salts, an excellent environmentally friendly construction material. Due to periodic filling of the PDSSH with the cool ternary gas mixture, the temperature of PDSSH walls and internal elements increases insignificantly, so that conventional (not heat-resistant) construction materials can be used for its production. It is thus implied that available propane or methane (natural gas) could be used in this waste processing process as starting fuels for PDSSH with further replacement by syngas generated during organic wastes gasification in the HSS environment.

Further work will be focused on replacing oxygen with air or oxygen-enriched air and on combining the PDSSH with a reactor for processing municipal and industrial wastes.

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