Reduction of DDT Run-Up Distance in a Two-Phase Flow by Combined Means

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Introduction

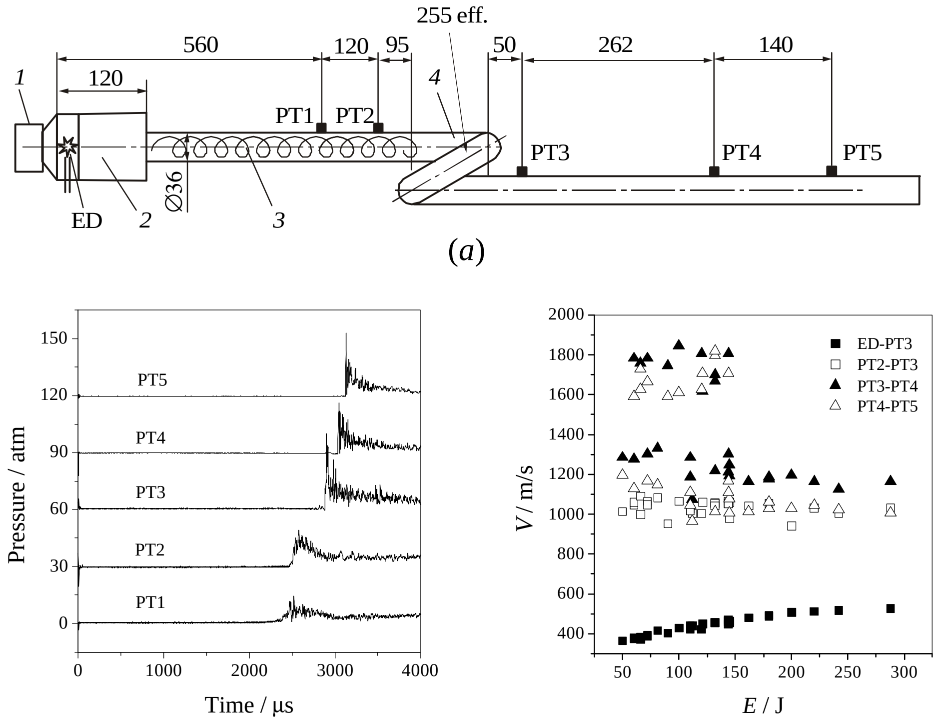
There exist several means to reduce deflagration-to-detonation transition (DDT) run-up distance in gaseous explosive mixtures. Laffitte [1, 2] demonstrated experimentally that DDT run-up distance decreases with decreasing tube diameter and increasing initial pressure. Shchelkin [3] revealed the important effect of aerodynamic conditions in the tube on the DDT run-up distance. He demonstrated that placing of regular obstructions in the form of wire spiral (Shchelkin spiral) in the tube results in a significant reduction of the run-up distance. Shchelkin and Sokolik [4] discovered the effect of DDT enhancement by preliminary thermal preparation of the explosive mixture. The use of a nanosecond corona discharge rather than arc-discharge as ignition source [5] allows significant reduction of the DDT run-up distance in a tube with Shchelkin spiral. Significant reduction of DDT run-up distance can be also attained by using traveling ignition sources to accelerate a weak shock wave to detonation intensity [6].

Contrary to DDT in gaseous mixtures, DDT in liquid fuel suspensions in air (oxygen) is eventually not studied so far. In the known experimental studies [7–9] heterogeneous (spray) detonation was initiated by strong sources — shock wave [7], gaseous detonation [8], or high-explosive charge [9]. In [10], detonation of liquid fuel suspension in air was initiated either with one or two powerful electric discharges. DDT in liquid fuel suspension in oxygen was detected in [11] and the run-up distance ranging from 20 to 100 tube diameters was reported. There is no available information on experimental observations of DDT in air suspensions of hydrocarbon fuels. In view of the growing interest in application of detonation to propulsion and power engineering [12], the studies of DDT enhancement in liquid fuel suspensions in air are getting increasingly important.

The objective of this paper is the reduction of DDT run-up distance in liquid fuel – air suspensions by various combined means.

Experimental Procedure and Results

As a basis for the current study, the experimental results of [10] are used. In [10], heterogeneous detonation of *n*-hexane–air mixture (equivalence ratio 1.3 ± 0.1) was registered in the horizontal, smooth-walled tube 51 mm in diameter and 1.5 m long at normal initial conditions. The tube was equipped with an air-assist atomizer at one end and a detonation arrester at the other. Fuel spray was ignited by a high-voltage electric discharger located at a distance of 60 mm downstream from the atomizer nozzle. At this distance, the measured drop size was in the range 5–6 μm. Starting from the discharge energy E equal approximately to 3300 J, direct detonation initiation in the two-phase flow was registered. A detonation wave propagated along the tube at the velocity of 1700–1800 m/s. At $1100 < E < 3300$ J, a decaying shock wave and a flame gradually decelerating along the tube were observed in experiments. At $E < 1100$ J, some acceleration of flame along the tube was detected, however pressure waves propagated at velocities not exceeding 400–450 m/s.



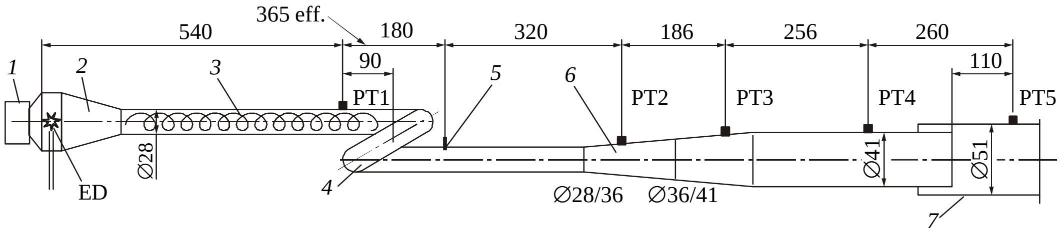
(*b*) (*c*)

Fig. 1 (*a*) Schematic of 36-millimeter tube with a new element — tube coil. (*b*) Pressure records by gauges PT1, PT2, ..., PT5 in the run with ignition energy of 60 J. (*c*) Measured shock wave velocities in a two-phase *n*-hexane–air mixture at different measuring segments as a function of the ignition energy

For decreasing the detonation initiation energy, it was decided to use tubes of 36 and 28 rather than 51 mm in diameter. In addition, to enhance turbulence intensity in the fuel spray exiting from the atomizer, a Shchelkin spiral was installed in the tube. The spiral was 600 mm long and was made of steel wire 4 mm in diameter with a pitch of 18 mm. Besides *n*-hexane, liquid *n*-heptane was used as a fuel.

At low ignition energy ranging from 130 to 240 J, the velocity of a shock wave exiting from the spiral attained 900–1000 m/s. Variation of the spiral wire diameter, spiral pitch and length did not virtually affect the shock wave intensity at these values of ignition energy.

To further amplify the resultant shock wave, a new element — tube coil — was installed downstream from the tube section with Shchelkin spiral. Figure 1*a* shows the schematic of the 36-millimeter tube equipped with air-assist atomizer *1*, discharge chamber *2*, electric discharger ED, Shchelkin spiral *3*, and tube coil *4*. Piezoelectric pressure gauges PT1–PT5 were used for registration of pressure wave profiles and for determining the wave propagation velocity. As the tube coil *4* introduces expansive and compressive surfaces to the propagating shock wave, it was expected that interaction between various wave systems would result in gasdynamic “focusing” phenomena promoting the detonation onset. Note that the “focusing” effect of tube coils has not been studied so far despite the phenomenon of gasdynamic “focusing” is well known for shock wave reflection from nonplanar ends of straight tubes.



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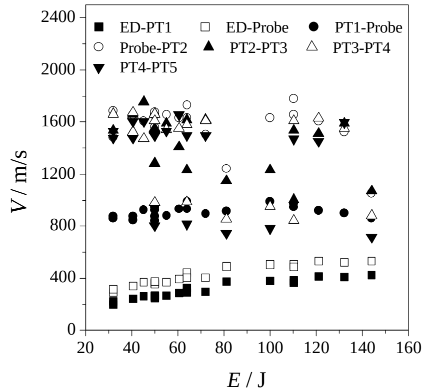

(*b*)

Fig. 2 (*a*) Schematic of 28-millimeter tube with tube coil and conical transition sections to the main tube 51 mm in diameter. (*b*) Measured shock wave velocities in a two-phase *n*-hexane–air mixture at different measuring segments as a function of ignition energy

Figure 1*b* shows pressure records by gauges PT1–PT5 in a run with ignition energy E = 60 J. Contrary to runs in a straight tube, a detonation wave is registered here at the exit from the tube coil (see the record of gauge PT3). Detonation arises inside the coil at a distance of about 1 m from the electric discharger (about 28 tube diameters). The detonation wave propagates till the end of the tube at the velocity of 1750 ± 20 m/s. Figure 1*c* shows the measured average pressure wave velocity V as a function of the ignition energy. The velocities at four measuring segments are shown: between discharger and gauge PT3 (segment ED–PT3), between gauges PT2 and PT3 (PT2–PT3), between gauges PT3 and PT4 (PT3–PT4), and between gauges PT4 and PT5 (PT4–PT5). At ignition energies ranging from 60 to 144 J, a detonation was registered at the exit from the tube coil in several runs. Detonation onset was occasional with the repeatability rate of about 50%. Interestingly, at higher values of ignition energy (144–300 J) detonation has not been ever detected. Probably, this phenomenon is explained by the fact that at high ignition energy the cumulating pressure wave (according to Shchelkin terminology) forms beyond the tube coil.

To further decrease the ignition energy required for detonation initiation inside the tube coil, a smaller 28-millimeter tube was used. Figure 2*a* shows a schematic of the experimental setup in which the minimal value — 30 J — of detonation initiation energy was obtained for both *n*-hexane–air and *n*-heptane–air two-phase mixtures. The setup contains air-assist atomizer *1*, discharge chamber *2*, electric discharger ED, Shchelkin spiral *3*, tube coil *4*, ionization probe *5*, two conical transition sections *6*, and 51-millimeter main tube *7*. Pressure records obtained in runs with this setup indicate that detonation arises inside the tube coil, transitions to the intermediate tube 41 mm in diameter and then to the main tube. At ignition energies ranging from 30 to 50 J detonation formed in the tube coil with high repeatability and always transitioned to the main tube (see Fig. 2*b*). At ignition energies from 50 to 130 J detonation not always transitioned to the main tube. At ignition energy ranging from 130 to 300 J detonation was not observed at all. The results were quite similar for both *n*-hexane and *n*-heptane fuel.

Structural variations in the setup of Fig. 2*a* (e.g., changing the shape of discharge chamber *2*, length of spiral *3*, shape of coil *4*, length of the tube section between the spiral end and the coil, and even length of the tube section between the coil end and transition cone) affected the explosion dynamics considerably. High repeatability of runs with detonation onset in the tube coil became possible due to careful optimization of the setup.

Concluding Remarks

Thus, replacement of the straight, smooth-walled tube 51 mm in diameter [10] by a combined tube shown in Fig. 2*a* allowed us to decrease the initiation energy of spray *n*-hexane–air and *n*-heptane–air detonations by two orders of magnitude, i.e., from 3300 to 30 J. In experiments with the tube coil, the electric discharge served as an ignition source rather than the source of the initiating blast wave. Therefore the results obtained can be interpreted as DDT in two-phase explosive mixtures. The run-up distance of DDT in the 28-millimeter tube appeared to be close to 1 m, i.e., to 36 tube diameters. Total length of the setup required for detonation transitioning to the main 51-millimeter tube is 1.8 m. Note for comparison, that DDT in gaseous propane–air mixture requires not less than 260 tube diameters in the case of straight and smooth-walled tube and more than 60 tube diameters in the case of straight tube with regular obstacles [12].

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