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RECENT RESEARCH ON THE ROTATING DETONATION AT WARSAW UNIVERSITY OF TECHNOLOGY

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Abstract

The paper describes the recent experimental investigation of detonation in a heterogeneous mixture of kerosene and oxidizer. Research was carried out in two different stands. For research on detonation limits, a number of short test tubes of differing inner diameter were used. Various mixtures of oxygen and nitrogen were used as an oxidant, from pure oxygen to the composition of air. The main goal of the study was to determine the minimum tube diameter required for direct initiation of detonation. From measurements, the pressure courses were obtained for three cases: direct initiation, initiation behind reflected wave and without initiation. The second part of the paper describes experimental research into the initiation and propagation of rotating detonation for heterogeneous kerosene and air mixtures. The research facility with main subsystems and exemplary results are shown and described.
Keywords: rotating detonation, RDE engine, heterogeneous mixture.

1. INTRODUCTION

In recent years, detonation as a combustion process in jet engines has attracted increased attention. Two possible detonation engine applications are taken into account: the Pulse Detonation Engine (PDE) and the Rotating Detonation Engine (RDE). Various gas and liquid fueled PDEs were built and tested. In a review paper, Roy et al. [1] showed a number of PDE engine designs, with different solutions as regards systems controlling the operation of the detonation chamber. Rasheed et al. [2] went a step further to describe the successful application of the study on an 8-tube PDE design as the can-annular combustion chamber working with a gas turbine. They used a stoichiometric mixture of ethylene and air at a mean mass flow rate of 3.628 kg/s. The tests lasted for at least 5 min and achieved power of 257 kW. RDE engine research started with initial attempts of Voitsekhovskii [3] and Voitsekhovskii et al. [4] at spin detonation in an axisymmetric channel for an acetylene-oxygen mixture. The same experiments attempted to repeat Nicholls and Cullen [5], but without positive results.

The next publications in this area come from the last 20 years: Bykovskii et al. [6], Bykovskii et al. [7-9]. They featured images of a velocity compensation method for a few fuels (hydrocarbons, hydrogen) with oxygen and with air in a different cylindrical chamber. Other publications on experiments with an RDE chamber were produced by Wolanski et al. [10] and Kindracki et al. [11].

In these studies, most of the experiments reported were conducted with gaseous fuels. To utilize detonation in jet engines, the use of liquid fuels (kerosene) is needed. The scale of the issues related to the detonation of heterogeneous mixtures illustrates the problems associated with it. In the papers of Vasil'ev et al. [12] and Bykovskii et al. [13] they state that about 340 kJ of energy is required for a mixture of propane and air to direct the initiation of spherical detonation (condensed explosive material was used). For a mixture of kerosene-air the energy required is even still higher. According to the research of Alekseev et al. [14] and Papavassiliou et al. [15] the value of energy is dependent on the size of the liquid fuel droplets. Successful tests of rotating detonation in heterogeneous mixtures were published by Bykovskii et al. [13] and Kindracki [16]. Many other authors describe problems with the use of liquid fuel for RDE engines, indicating fundamental problems with the design of the detonation chamber. This paper describes efforts at Warsaw University of Technology in experimental works aimed at developing detonation engine design.

2. RESEARCH ON DETONATION IN A KEROSENE-OXIDIZER MIXTURE

2.1. Research on detonation limits

The main element of the test facility was a steel tube, length 1050 mm, with a circular cross-section and installed in a vertical position. Four tubes of various diameters were used. The upper end of the tube was closed by a fuel injector. The lower end of the tube was closed by an end wall or, in some of the experiments, by the axial initiator. The tube was equipped with a few slots for temperature and pressure transducers. The tube was equipped with heaters (they were connected to a thermo-regulator to control the process), used to heat the oxidizer to a certain temperature. Figure 1 shows a photograph and a schematic diagram of the test stand.

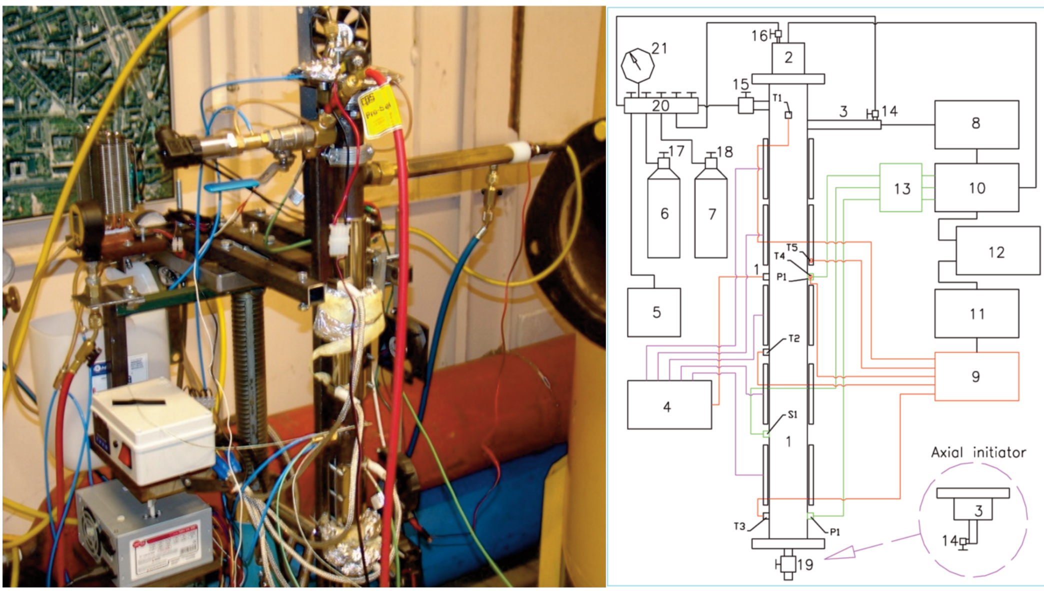


Fig. 1. Research stand for experimental determination of detonation limits for kerosene – oxidizer mixture at elevated temperatures: P1÷P3 – pressure gauges (Kistler 306B); T1÷T5 – thermocouples; 1 – tube; 2 – kerosene injector; 3 – initiator; 4 – temperature control system; 5 – vacuum pomp; 6 – bottle with oxidizer; 7 – bottle with nitrogen; 8 – ignition system; 9 – thermocouple amplifier; 10, 11 – acquisition card (NI PCI 6115, NI USB 6259); 12 – computer; 13 – pressure sensor amplifiers; 14¸19 – valves; 20 – control valve unit; 21 – manometer [Kindracki, 2012]

K-type thermocouples installed at three points inside the tube and the acquisition card USB 6259 NI continuously monitored the temperature of the oxidizer. Typical temperature recordings for a single experimental day are shown on figure 2; the graph showing changes of oxidizer temperature during filling, exhausting and experiment time. For pressure measurements, fast Kistler 603B transducers, amplifiers and a high speed 4-channel measurement card, NI PCI 6115 were used. A high pressure oxidizer tank was used to fill the tube with oxidizer. The oxidizer was prepared in a high pressure bottle from oxygen and nitrogen, using the partial pressure method. In the described experiment oxidizer with various concentrations of oxygen was used, in the range 100-23% oxygen. For fuel injection, an electrically-controlled plain orifice injector was used. For pressurization an additional tank with nitrogen with precise valve control was chosen. Nitrogen pressure was typically 6-7 bar. To initiate the process of detonation in the test tube a gas initiator was used, which can be mounted in two positions: perpendicular to the test tube – close to the fuel injector – or axial at the bottom end of the test tube. Stoichiometric acetylene - oxygen mixture with different pressure to change initiation energy was used. Initiator and tube volume were separated by a thin plastic membrane with a thickness of 0.1 mm, which was destroyed during each experiment.

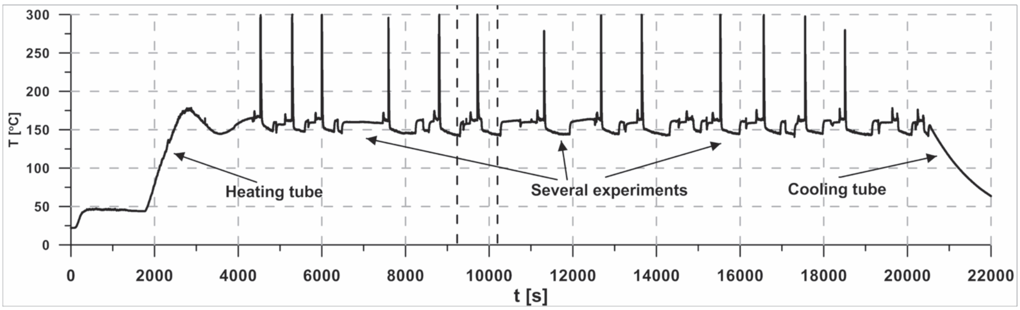


Fig. 2. Typical oxidizer temperature recording for a single experimental day [Kindracki [17].

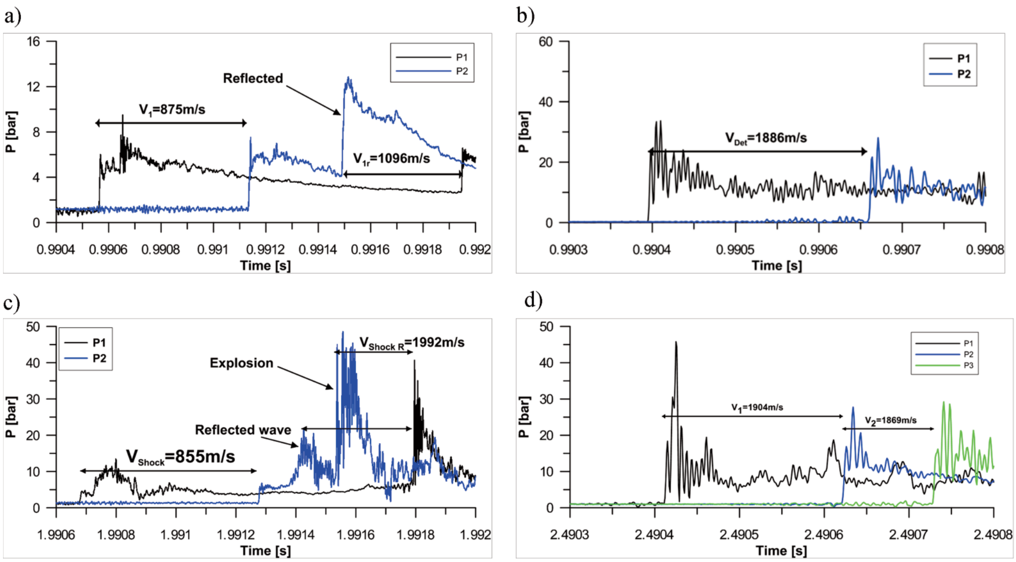


Fig. 3 Experimental results: a) tube ϕ44mm, oxidizer 40%O_2+60%N_2 – shock wave; b) tube ϕ24.5mm, oxidizer100%O_2 – direct initiation; c) tube ϕ35.7mm, oxidizer 50%O_2+50%N_2 – initiation behind reflected shock wave; d) tube ϕ55mm, oxidizer – air – direct initiation [Kindracki, 2012].

The study was conducted for a few different oxygen-nitrogen compositions. For a given tube, experiments were carried out until a combination of tube diameter – oxidizer was found for which no direct initiation of detonation was obtained. At this point, the experiments were stopped and the tube was changed. Figure 3 shows some characteristic cases of experiments for different tubes. Three different cases are shown: propagation of the shock waves, direct initiation of heterogeneous detonation and initiation some distance behind the reflected wave.

Figure 4 summarizes the experimental results obtained for different kinds of initiators with different energies and for different tubes. The graph was presented using the coordinates of the share of oxygen and the diameter of the tube. Two curves divide all the space on the graph into three sectors: direct initiation of detonation, initiation behind the reflected shock wave and without initiation of detonation. It should be mentioned that the experimental tube was short, so these results are not indicative of detonation stability over long distances. As regards the design of a detonation chamber for a jet engine, the most important aspect is the relationship between tube diameter and air as an oxidizer. This value allows one to design the geometry of the chamber to increase the probability of successful initiation of rotating detonation for a heterogeneous mixture.

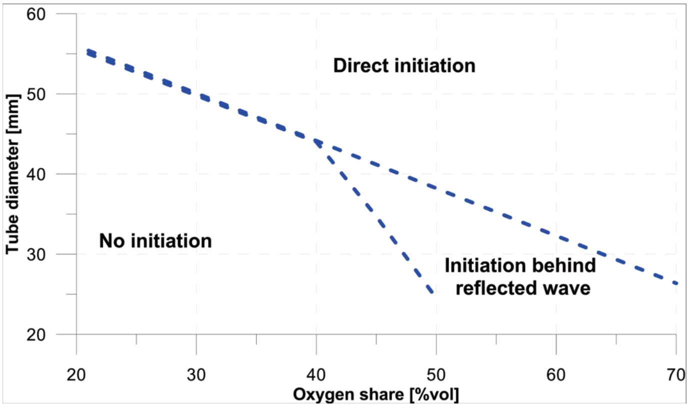


Fig. 4. The possibility of obtaining direct initiation of detonation as a function of oxygen in the oxidizer and the diameter of the tube [Kindracki [17].

2.2. Rotating Detonation in a Kerosene-Air Mixture

The main element of the test bench was an aluminum alloy chamber of the outer diameter 168 mm and length 120 mm, installed in a horizontal position to the damp tank. One end of the chamber was closed by an air injector, the second was open. The chamber was equipped with dual fuel systems: hydrogen and liquid kerosene. Injectors of both fuels were placed perpendicular to the axis of the chamber. Hydrogen was injected by 90 simple holes along the curvature of the inner chamber wall. Kerosene was injected by 12 swirl injectors controlled by one electromagnetic valve. Air was supplied by a long inlet connected to the air tank by four pipes. The air mass flow rate can be changed by altering the pressure inside the tank. A gas initiator placed perpendicular to the wall chamber was used to initiate the process of detonation in the main chamber. The initiator and chamber volume were separated by a thin plastic membrane. The chamber and mixture component manifolds were equipped with several slots for the installation of pressure and temperature sensors. The sensors used were: Kistler 603B, Keller sensors PAA-23/25 and PD-23 and they measured the pressure with 0.5% FS accuracy. Each mixture component line was equipped with appropriate sensors to enable mass flow rate calculation.

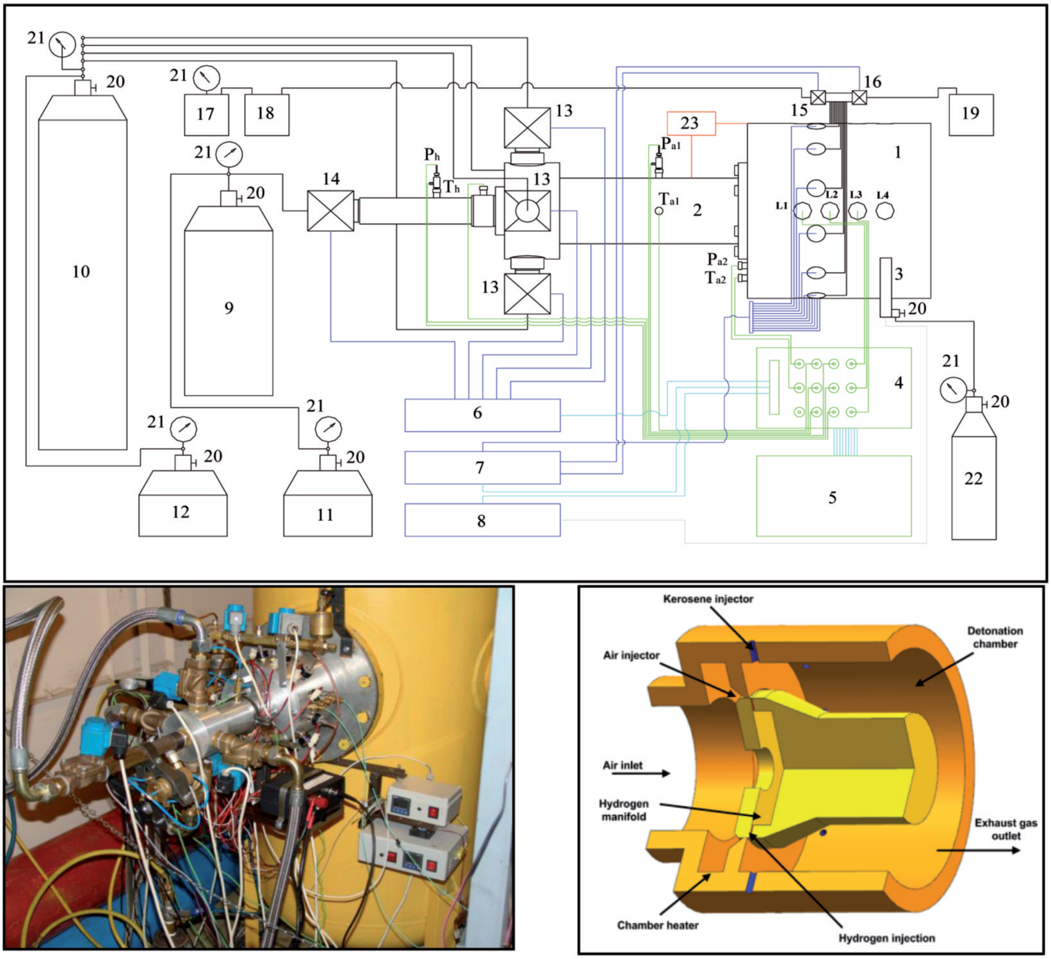


Fig. 5. The experimental setup view and schematic diagram: 1 – detonation chamber, 2 – air heater, 3 – initiating device, 4 – acquisition card, 5 – computer, 6, 7 – DC power charger, 8 – spark plug controller, 9 – hydrogen low pressure tank, 10 – air low pressure tank, 11 – hydrogen high pressure tank, 13 – air control valves, 14 – hydrogen control valve, 15,16 – kerosene control valves, 17 – nitrogen tank (for kerosene pressure fed system), 18 – kerosene tank, 19 – kerosene overflow tank, 20 – ball valve, 21 – manometer, 22 – tank with initiating mixture (acetylene with oxygen), 23 – heater control system [Kindracki, 2012]

Figure 6 shows the course of detonation propagation recorded by three pressure transducers placed in one plane in 90 degree angle separation. The upper part of the graph shows the different timestamp and different character of propagation. These mean that the detonation wave can change propagation mode during one experiment depending on the local conditions and composition of the mixture. In this experimental setup a finite volume tank was used for the air. The pressure changes a little during the experiment and changes the global equivalence ratio of the mixture. Additionally, the local mixing of fuel and air can affect the propagation mode.

Figure 7 shows the calculated propagation velocity for three transducers. Figure 8 shows exemplary results of the propagation and velocity for different equivalence ratios of the heterogeneous mixture.

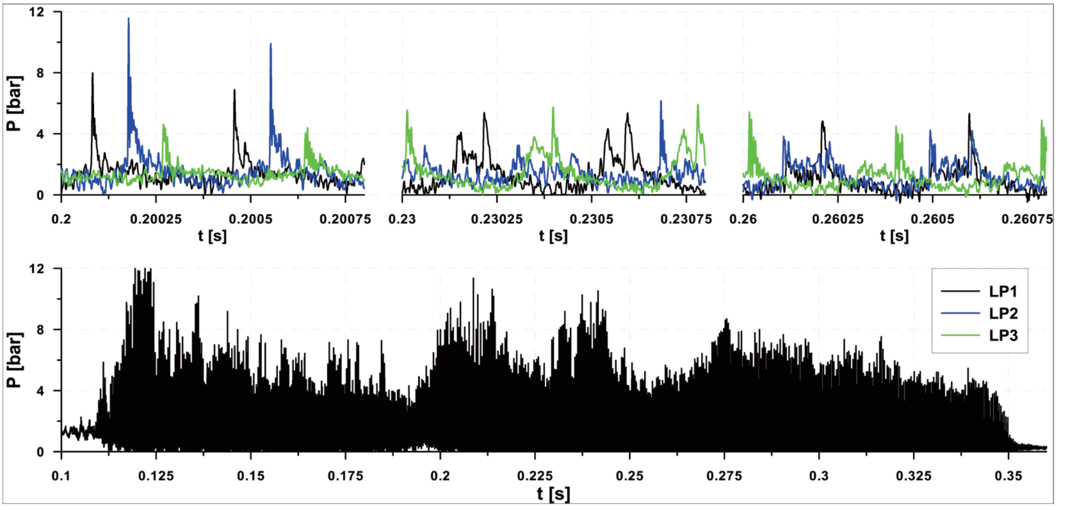


Fig. 6. Propagation of rotating detonation in kerosene-air mixture with small addition of hydrogen – pressure history: mean parameters in the chamber: 1.4bar, 0.45kg/s, equivalence ratio ≈ 1 [Kindracki, 2012]

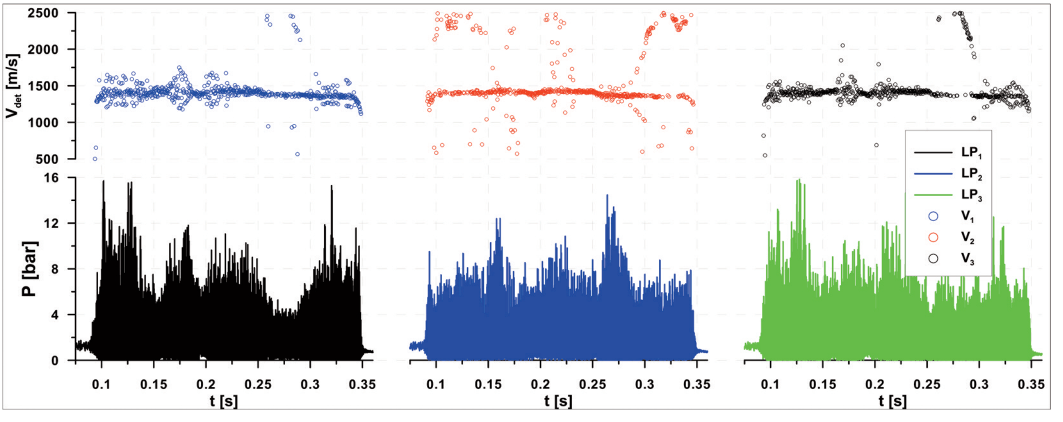
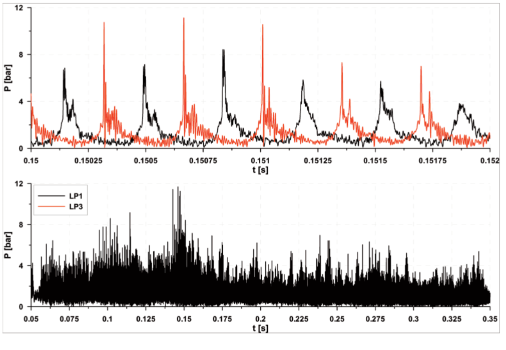
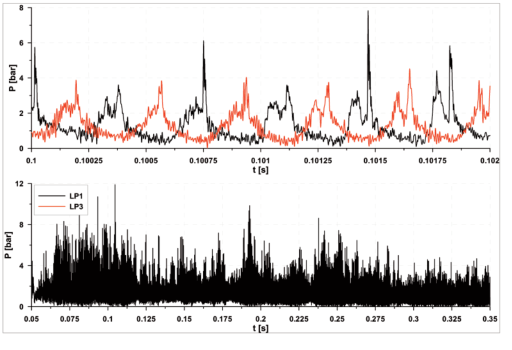


Fig. 7. Propagation of rotating detonation in kerosene-air mixture with small addition of hydrogen – velocity history (different sensor positions): mean parameters in the chamber: 1.4bar, 0.45kg/s, equivalence ratio ≈ 1 [Kindracki, 2012]

a)



b)



c)

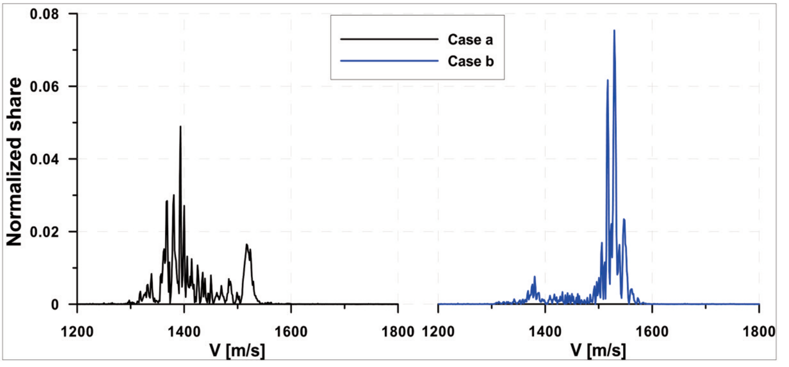


Fig. 8. Initiation and propagation rotating detonation for kerosene – air mixture with small addition hydrogen for different equivalence ratio (ϕ): a) propagation detonation for ϕ≈1.9 (kerosene injection pressure 6.5bar); b) propagation detonation for ϕ≈2.05 (kerosene injection pressure 8.9bar); c) comparison of velocity of propagation [Kindracki, 2012]

3. SUMMARY AND CONCLUSION

This paper presents a current research problem and results on rotating detonation in an RDE context. Two original research stands and exemplary results were presented. For the detonation limits in kerosene-oxidizer mixture at elevated temperatures, direct initiation of detonation was obtained for each test tube for some range of oxygen content in the oxidant. Direct initiation of detonation for air as an oxidizer was obtained for the tubes with diameters of 44 mm and 55 mm with an axial initiator.

Detonation chamber geometry was successfully designed for a heterogeneous mixture of liquid kerosene and gaseous air. A small addition of gaseous hydrogen improved the detonability properties of the heterogeneous mixture. The experiments were carried out on an axisymmetric chamber with an outer diameter of 160mm, for a different equivalence ratio mixture. Propagation of rotating detonation was not achieved with the mixture of liquid kerosene and gaseous air for ambient temperatures. That was caused by problems with proper fragmentation and evaporation of liquid fuel at room temperature. To solve this problem the air and fuel need to be pre-heated. A velocity deficit of about 25% was determined for rotating detonation in a heterogeneous mixture. The value is comparable with literature data. There is need for more experimental and numerical efforts on a larger scale with a detonation chamber fed by hot air and liquid kerosene to provide more data for design of a real detonation chamber and to compare performance with a classic jet engine deflagration combustion chamber.

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WYBRANE BADANIA EKSPERYMENTALNE WIRUJĄCEJ DETONACJI W POLITECHNICE WARSZAWSKIEJ

Streszczenie

W artykule przedstawiono wybrane badania eksperymentalne wirującej detonacji, prowadzone na Politechnice Warszawskiej. Przedstawiono dwa stanowiska badawcze, na których prowadzono badania procesu detonacji: granic występowania zjawiska detonacji dla mieszaniny ciekłej nafty i utleniacza oraz inicjacji wirowania detonacji w komorze osiowosymetrycznej. Na pierwszym stanowisku, wyznaczono zakres detonacyjności mieszaniny z wykorzystaniem różnych utleniaczy, zaczynając od czystego tlenu a kończąc na powietrzu. Uzyskane wyniki podzielono na trzy zakresy: bezpośredniej inicjacji fali detonacyjnej, inicjacji za falą uderzeniową, odbitą i brak detonacji, jako funkcję składu utleniacza oraz geometrii komory (rury detonacyjnej). W drugiej części opisano proces inicjacji wirującej detonacji w specjalnie zaprojektowanej walcowej, osiowosymetrycznej komorze detonacyjnej, z powietrzem, jako utleniaczem. Pokazano przykładowe eksperymenty oraz potwierdzono występowanie deficytu prędkości, który wynosił nawet 25%.
Słowa kluczowe: wirująca detonacja, silnik detonacyjny RDE, mieszaniny heterogeniczne.