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Experimental research on rotating detonation in liquid fuel–gaseous air mixtures

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ABSTRACT

This paper describes experimental research into the initiation and propagation of rotating detonation for liquid kerosene and gaseous air mixtures. The research facility with main subsystems is described: fuel and air feeding system, initiation and measurement system. The methods of measurement and calculation of the mass flow rate for each mixture component and methods of calculation of propagation velocity are presented. Pressure inside the detonation chamber was measured by up to three, fast Kistler transducers, which were placed in one line along the chamber or in one plane around the circumference. Propagation of rotating detonation was obtained for a mixture of liquid kerosene and air and a small addition of gaseous hydrogen (below the lean limit). In some experiments, liquid isopropyl nitrate was added to kerosene and its influence to enhance the detonation sensitivity of the kerosene–air mixture was checked. Also a velocity deficit of 20–25% was determined for rotating detonation for the examined heterogeneous mixture.

1. Introduction

Applied detonation as a combustion process in jet engine combustors has been studied for several decades. A pioneering role was played by the Russians (Voitsekhovskii [1], Voitsekhovskii et al. [2]). They obtained a rotating detonation wave for an oxy–acetylene mixture in an axisymmetric channel. Nicholls et al. [3,4] presented the possibility of designing a rocket engine with rotating detonation as a combustion process for gaseous and heterogeneous mixtures. An undoubted advantage of this concept is the increased thermal efficiency of the process due to the fact that it is carried out at quasi-constant volume, as compared to the classical jet engine combustion chamber, where combustion takes place at constant pressure. An additional advantage of the detonation process in the combustion chamber is that flame front (detonation front) can propagate in stable fashion even for lean mixtures, which reduces the average temperature of combustion. The reduction in temperature influences the production of harmful gases such as nitrogen oxides and can simplify the cooling system or reduce cooling requirements.

There are two main ways of using detonation processes to build the detonation engine. The first one uses a long tube where detonation propagates in a fresh mixture and the outflow of exhaust gases can be used to drive a turbine [5] or directly generate thrust in the de Laval nozzle [6,7]. The second one is to use the possibility of generating a rotating detonation wave in a closed channel. This makes it possible to design a short length combustion chamber, thereby reducing the weight and manufacturing costs of the chamber. The main problem in this combustion chamber is the correct selection of the thermodynamic parameters of the mixture and determining useful geometry of the chamber. Additionally, this solution makes it possible to simplify the fuel feeding system and reduce the number of initiations of detonation to the one at the start of the chamber operation, which contrasts with PDE where initiation (ignition) must occur in each cycle. The RDE chamber fuel and oxidant are fed continuously, so the exhaust gases are also produced in a continuous manner. On the other hand propagation of detonation in the PDE is cyclical, because it takes into account the process of supplying the fresh mixture and exhaust gases. Thus the PDE solution has much lower operation frequency than RDE. The low frequency problem is resolved by the use of multi-tube systems, which complicate the design and render control difficult.

For the RDE solution presented, the experimental work or numerical calculations were usually for gaseous fuel: hydrocarbon or hydrogen with an oxidant in the form of oxygen (Kindracki et al. [8]; Wolanski et al. [9]; Bykovskii et al. [10]) or air (Bykovskii et al. [11]; Bykovskii et al. [12]; Kindracki et al. [13]; Kindracki and Wolanski [14]). Falempin and Le Naour [15] presented research on designing a detonation engine (PDE or RDE) for rocket propulsion.

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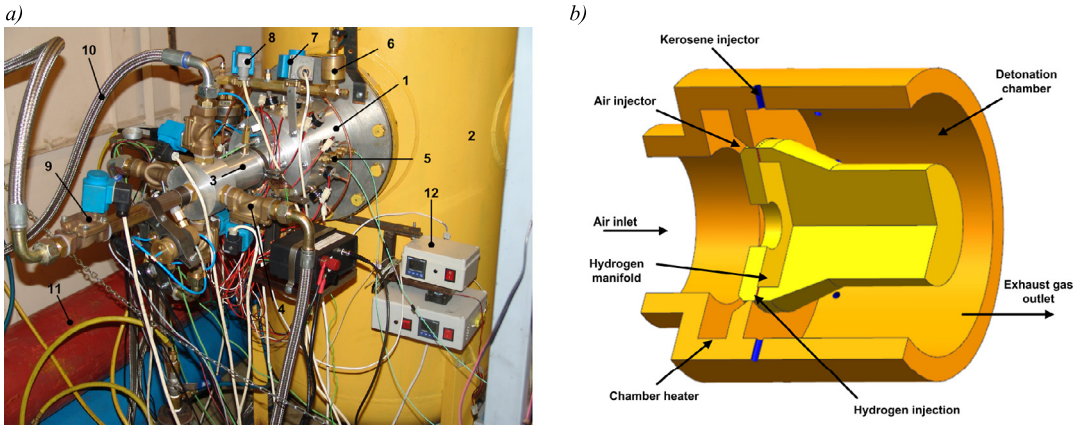

Fig. 1. The experimental setup: a) view of the research stand: 1 – detonation chamber, 2 – dump tank, 3 – air manifold, 4 – air electromagnetic valves, 5 – pressure transducers (Kistler 603B), 6 – kerosene tank, 7 – kerosene main valve, 8 – kerosene drain valve, 9 – hydrogen electromagnetic valve, 10 – air supply lines, 11 – air tank, 12 – chamber temperature controller; b) scheme of the detonation chamber.

The first step in this project was to design a ground demonstrator for a liquid hydrogen liquid oxygen mixture. Bykovskii et al. [16] described experimental research for liquid kerosene with oxidizer (50% O_2 and 50% N_2) in a detonation chamber with a diameter of 306 mm. They also used a mixture of propane and air and compared results against a kerosene mixture. In both cases 0.2 g of high explosive material was used to initiate detonation.

More PDE engine research using liquid fuel (kerosene, *n*-heptane, etc.) was conducted. Pintgen and Shepherd [17] described research on partially oxidized jet fuel for a single tube PDE engine and its influence on performance. Partially oxidized fuel reduced the nominal impulse by up to 60% when the partial oxidation to total mass fuel ratio was 2. Additionally, they reported numerical analysis and experimental research on the detonation properties (cell size) for the mixture with partially oxidized kerosene. Frolov [18] described research on a liquid fuel (*n*-heptane and *n*-hexane) and gaseous air PDE demonstrator. A special pre-detonator with Shchelkin spiral, tube coil and low ignition energy was used to initiate detonation in the main tube. The cold fuel was injected by an air-assist liquid atomizer, which provided very fine fuel drops in a short distance (5–6 μm at a distance of 70 mm from the injector nozzle). Kailasanath [19] presented a review of experimental research into low-vapor liquid fuel detonation parameters. A few explanations of the problem with a deficit on propagation velocity (for large droplets) compared to the gas-phase velocity were taken account of. Heating the mixture, prevaporization and injecting of small droplets help initiate the detonation process. Fan et al. [20] presented results from experimental research for a heterogeneous C_8H_{16}–air mixture. They tested three different geometries with simple initiation methods (low-energy ignition system and Shchelkin spiral). The tube can successfully operate with a frequency up to 36 Hz.

This paper describes experiments of initiation of rotating detonation for liquid kerosene with the addition of hydrogen and/or isopropyl nitrate. Development of a detonation chamber for liquid fuel will be a key issue in the implementation of this kind of propulsion system (RDE) for use in the aerospace industry.

2. The research facility

The main element of the test bench (Fig. 1) was an aluminum alloy chamber with an outer diameter of 168 mm and length 120 mm, installed in a horizontal position. One end of the chamber was closed by an air injector, the second was open. The chamber was equipped with two fuel systems: for gas fuel – hydrogen and liquid fuel – kerosene. Injectors of both systems were placed perpendicularly to the main flow in 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 individually by an electric coil or fed from a common manifold and controlled by one electromagnetic valve. The kerosene manifold was equipped with an additional drain valve, used in each experiment for fast and effective fuel shutoff. The air manifold was connected to two bottles by four electromagnetic valves, which made it possible to use four levels of air mass flow rate. Additionally, the air mass flow rate can be changed by altering the pressure inside the bottle in the range 5–12 bar. A gas initiator was used to initiate the process of detonation in the chamber. The initiator was placed perpendicularly to the wall chamber, at a distance of 42 mm from the air injector. It was filled with a stoichiometric mixture of oxygen and acetylene at the specified pressure (usually 3 bar). The initiation mixture was prepared in a special tank, using the partial pressure method, at least 24 hours before the experiment (to ensure the mixture is homogeneous). The initiator and chamber volume were separated by a thin plastic membrane with a thickness of 0.1 mm, which was destroyed during each experiment. Initiation of this kind was examined for different oxidizers on another research stand, and was described in the paper [21]. The mixture was ignited by an ordinary spark plug, using a control system equipped with a National Instruments acquisition card. In some cases the chamber was heated by two special heaters placed inside the air manifold and near to the air injector. The maximum wall chamber temperature reached was 333–338 K. The wall temperature was increased to boost the degree of evaporation of the kerosene.

The chamber and manifolds were equipped with several slots for the installation of pressure and temperature sensors. The pressure transducers used in the experiments were: fast Kistler sensors to measure the pressure inside the chamber (type 603B) and Keller sensors PAA-23/25 (absolute static pressure) and PD-23 (differential pressure) to measure the pressure inside the manifolds. 0.5% full scale accuracy was used for the sensors. These measurements and indication of the static temperature were used to calculate the density and mass flow rate for air and hydrogen (using the widely known continuity equation). All the measurements were performed using two acquisition cards supplied by National Instruments: PCI 6115 and USB 6259. Fig. 1 shows a view of the test bench. Fig. 2a and Fig. 3a show a view of the pressure sensors and the point at which the air and hydrogen were measured. Fig. 2b and Fig. 3b show the course of the measured pressures and calculated mass flow rate as a function of time.