

JP-10 Vapour Detonations at Elevated Pressures and Temperatures

F. Zhang, S. B. Murray, and K. Gerrard

Defence Research Establishment Suffield

PO 4000 Station Main, Medicine Hat, AB T1A 8K6 Canada

fzhang@dres.dnd.ca

There has recently been interest in employing hydrocarbon missile fuels in pulse detonation engines where fuel storability and safety are prime concerns [1-3]. These synthesized hydrocarbon liquid fuels such as JP-10 possess low vapour pressures and high carbon-to-hydrogen ratios, and therefore have low detonability. In the vapour phase at 1 atm initial pressure, the detonation cell size of stoichiometric JP-10 in air is approximately 5 cm [3], which is more than three times that of hydrogen. However, under stagnation flow conditions at flight Mach numbers of interest, pressures can be increased several times, thus resulting in an increase in the detonability with a detonation cell size decreased towards that of hydrogen. This trend was indicated in some preliminary results of a previous paper [3]. The practical engine operation conditions lie between atmospheric pressure and the stagnation pressure at the maximum flight Mach number. Hence, it is necessary to know the detonation properties of the fuel over a wide range of initial pressures and temperatures. It is also necessary to obtain the detonation cell sizes at various mixture equivalence ratios in determining an optimal ratio of fuel to air.

From the fundamental point of view, the influence of the initial temperature on the detonability of gas-phase mixtures has not been clearly resolved. For hydrocarbon-air mixtures, Tiezen et al. [4] found a weak dependence of the detonation cell size on the temperature over the range from 293 K to 373 K. This is probably due to the narrow temperature range and the relatively low temperature values that are insufficient to cause a significant effect on the Arrhenius-like kinetics. Using hydrogen-air mixtures, Ciccarelli et al. [5] reported that an increase in temperature from 293 K to 650 K at 100 kPa results in a decrease in the detonation cell size. The decrease in the cell size becomes considerably significant when the mixture departs from the stoichiometric ratio or when the steam diluent is increased. To the contrary, Auffret et al. [6-7] found that the detonation cell size increases with temperature from 293 K to 600 K for stoichiometric ethylene-oxygen mixtures and from 293 K to 500 K for stoichiometric acetylene-oxygen mixtures at 5 to 100 kPa. In particular, the influence of temperature on the detonation cell size becomes insignificant when the acetylene-oxygen mixtures become lean. Theoretically, the solution for the dependence of the detonation cell size on temperature at fixed pressure is imbedded in the mixture chemistry and the competition between the density and temperature in the Arrhenius-like kinetics. However, these conflicting observations thus require more experimental studies to enhance our understanding of the relation of the detonation cell size and detonability with initial temperature for various fuels over a range of mixture equivalence ratio.

The present paper is focused on investigating the detonation properties of JP-10 vapour-air mixtures at pressures ranging from 103 kPa to 500 kPa and temperatures up to 550 K with various mixture equivalence ratios. A heated detonation tube 20 cm in inner diameter was designed for this purpose, shown schematically in Fig. 1. The facility, which is made of a

Schedule 160 steel pipe for sustaining a static pressure of 270 atm at 38 °C, consists of a 1 m driver section, a 6.1 m test section including a 0.76 m smoke foil section at its end, and a 6.1 m relief section. Aluminum diaphragms are used to separate the driver section from the test section and the test section from the relief section. The length of the driver can be adjusted between 0.5 m and 1 m to ensure a minimum length of driver for achieving a CJ detonation wave within a short distance in the test section. The driver section can be filled with equimolar acetylene-oxygen mixtures at various initial pressures. Initiation of the driver gas can be achieved by a spark connected to an 8 J Reynolds ignition system or by chemical detonators. Electric tape heaters are strapped to the outside surface and distributed uniformly along the entire length of the test section as well as the adjacent part of the driver and the relief section. These heaters enable the test section to be heated up to 700 °C. Gauge ports are located at 0.5 m intervals along the test section and ion gauges are used to measure the flame velocity. To record the detonation cell size, an aluminum smoke foil, 0.66 m long and 0.63 m wide, is mounted cylindrically on the inner surface of the smoke foil section located at the end of the test section. The final temperature of the vapour test mixture is automatically controlled to within ± 2 °C using two thermocouples and temperature controllers. The thermocouples are positioned to read the temperature of the test mixture, near the test-section centerline, at two locations along the length of the test section. The temperature of the detonation tube surface is periodically monitored during the heating process along the entire length of the test section. A 0.5 litre stainless steel vessel containing pre-measured liquid fuel is connected to the test section through a series of components including preset needle valves, isolating solenoid valves, and gradually heated tubing. The desired test gas composition is achieved using the method of partial pressures. The gas is then recirculated for a period of time to ensure uniform mixing. The recirculation system temperature is automatically controlled to within 5 °C of the test section temperature. Finally, the relief section serves to reduce the possibility of undesired pre-compression and the subsequent deflagration-detonation transition in the Craven and Greig scenario, which can cause very high pressures [8].

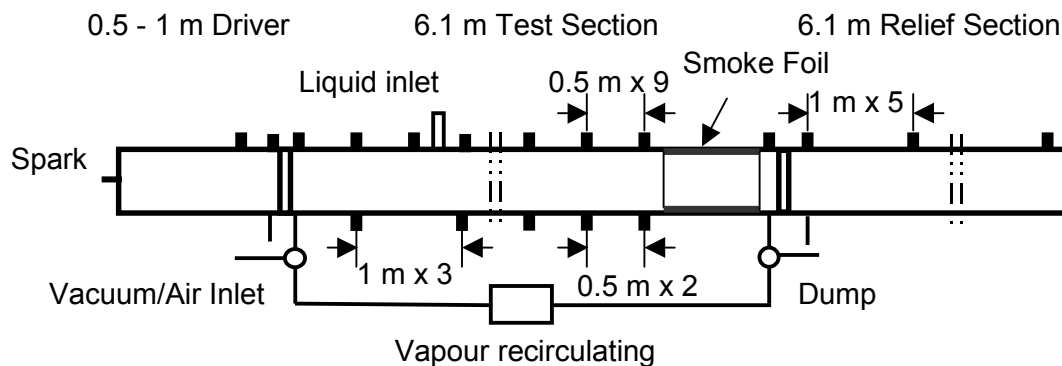


Figure 1. Schematic of the heated detonation tube.

The test procedure begins by first evacuating the test section and filling it with dry air to about 0.5 atm. It is subsequently heated to the desired elevated temperature over a period of 1 to 1.5 hours. When the target temperature is reached, the liquid fuel is introduced into the test

section using the preset needle valves and isolating solenoid valves. After the complete vaporization of the liquid fuel, the test section is filled to a test initial pressure with dry air. The mixture is then recirculated for 30 minutes while the facility remains heated. After recirculation of the test vapour mixture, the driver is filled, in less than 5 minutes, with an equimolar acetylene-oxygen mixture to 0.6 – 0.7 times the test vapour initial pressure. Detonation of the test vapour is finally initiated by the acetylene-oxygen detonation wave originating in the driver and transmitted through the bursted diaphragm.

Preliminary experiments for the stoichiometric JP-10 vapour-air mixture were performed using a field setup at an initial temperature of 503 K and pressures of 155 kPa and 210 kPa. The smoke foil records are displayed in Fig. 2, which indicates that a multi-headed detonation with a transverse wave configuration propagates in the JP-10 vapour-air mixture. The measured detonation cell widths are summarized in Table 1 with a maximum deviation of about ± 20 %. The detonation wave in the stoichiometric mixture of JP-10 vapour and air has an average cell width of 3.1 cm for the initial pressure of 155 kPa and 2.1 cm for 210 kPa. For the experiment at 155 kPa, the detonation velocity measured upstream of the smoke foil is 1742 m/s which is very close to the calculated equilibrium CJ velocity within a deviation of -2% . At 210 kPa, the detonation velocity obtained upstream of the smoke foil is 1810 m/s, which deviates from the equilibrium CJ velocity by $+2\%$ (see Table 1).

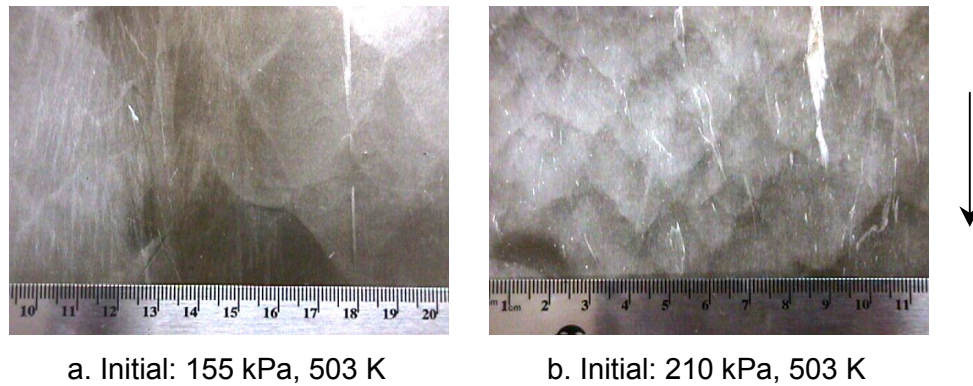


Figure 2. Smoke foil record of cellular detonation for stoichiometric JP-10 vapour-air at 503 K. The direction of detonation propagation is downwards.

Table 1. Detonation data for stoichiometric JP-10 vapour-air mixture at 503 K and elevated pressures

Trial No.	Initial pressure, kPa	Mean cell width*, mm	Standard deviation of cell width, mm	Detonation velocity, m/s	CJ detonation velocity, m/s
1	155	31	5.0	1742	1777
2	210	21	3.5	-	1783
3	210	21	4.2	1810	1783

* The cell width was measured as the distance between the two vertexes.

The detonation cell widths measured for the stoichiometric JP-10 vapour-air mixture at various pressures and 503 K are displayed in Fig. 3, together with the data at 100 kPa and 408 K from [3]. Within the initial pressure range between 100 and 210 kPa, the detonation cell width is approximately inversely proportional to the initial pressure. This correlation is in good agreement with observations for various gas mixtures in the literature. The correlation of the cell size with the initial pressure is to be further investigated up to 400 and 500 kPa at various temperatures and mixture equivalence ratios. It is noticed in Fig. 3 for the preliminary tests that the influence of the temperature on the cell size can be embedded in the error range. To determine the dependence of the detonation cell size on temperature and the optimum fuel-to-air ratio for engine operation conditions, measurements for the detonation cell size are currently being conducted systematically up to the auto-ignition point and also for off-stoichiometric conditions.

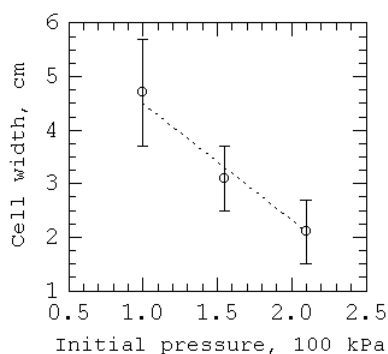


Figure 3. Correlation between the detonation cell width and the initial pressure for stoichiometric JP-10 vapour-air. $T = 408\text{K}$ for 100 kPa; $T = 503\text{K}$ for 155 to 210 kPa.

References:

1. Brophy C.M., Netzer D.W., and Froster D., "Detonation studies of JP-10 with oxygen and air for pulse detonation engine development," AIAA-98-4003, 1998.
2. Brophy C.M., and Netzer D.W., "Effects of ignition characteristics and geometry on the performance of a JP-10/O₂ fueled pulse detonation engine," AIAA-99-2635, 1999.
3. Akbar, R., Thibault, P.A., Harris, P.G., Lussier, L.-S., Zhang, F., Murray, S.B., and Gerrard, K., "Detonation properties of unsensitized and sensitized JP-10 and Jet A fuels in air for pulse detonation engines," AIAA-2000-3592, 2000.
4. Tieszen, S.R., Stamps, D.W., Westbrook, C.K., and Pitz, W.J. "Gaseous hydrocarbon – air detonations," Combustion and Flame, 84: 376-390, 1991.
5. Ciccarelli, G., Ginsberg T., Boccio J., Economos C., Sato K., and Kinoshita M., "Detonation cell size measurements and predictions in hydrogen-air-steam mixtures at elevated temperatures," Combustion and Flame, 99: 212-220, 1994.
6. Auffret, Y., Desbordes, D., and Presles, H.N., "Detonation structure of C₂H₄-O₂-Ar mixtures at elevated initial temperature," Shock Waves, 9: 107-111, 1999.
7. Auffret, Y., Desbordes, D., and Presles, H.N., "Detonation structure and detonability of C₂H₂-O₂ mixtures at elevated initial temperature," Shock Waves, in press, 2000.
8. Zhang, F., Thibault, P.A., and Murray, S.B., "Transition from deflagration to detonation in an end multiphase slug," Combustion and Flame 114:13-25, 1998.