Combustion Wave Characteristics of LPG-Oxygen Mixture behind Porous Media Model

Jayan Sentanuhady*, Jannati Adnin Tuasikal

Dept. of Mechanical and Industrial Engineering, Faculty of Engineering, Universitas Gadjah Mada

Jalan Grafika No. 2, Kampus UGM, Yogyakarta, 55281, Indonesia

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Abstract: LPG-air mixture enriched with oxygen is usually used for generating heat in industry sector. However, it possibles that LPG-oxygen will mix and react independently and the mixture could generate detonation wave. This condition could harm people, environment, and piping system, thus detonation quenching to guarantee safety becomes very important. The aim of this experiment is investigating detonation quenching phenomena behind stainless steel porous media model.

This experiment used detonation test tube with 50 mm of inner diameter and 6000 mm of total length, which consists of two sections, 1000 mm in length of driver section and 5000 mm in length of driven section. Driver section and driven section are separated by mylar film to prevent mixing between driver gas and driven gas which usually consists different gas mixture and different gas pressure. The driver section contains stoichiometric hydrogen-oxygen mixture at constant initial pressure, while the driven section contains stoichiometric mixture of LPG and oxygen at initial pressure varied from 10 to 100 kPa with interval of 10. Stainless steel porous media with mass of 10 gram was inserted in a perforated cylindrical case. Observation of detonation wave propagation was done at upstream and downstream of the model.

Four mechanisms of combustion wave propagation were observed in the downstream of porous medium model, which are (a) deflagration quenching, (b) detonation quenching, (c) detonation reinitiation, and (d) detonation transmission. Deflagration quenching occurred at initial pressure up to 10 kPa and detonation quenching occurred at initial pressure between 10-20 kPa. However, if the initial pressure is increased to be 30 up to 50, detonation will be reinitiated and if the initial pressure is increased higher than 50 kPa, detonation will be transmitted directly. This experiment, also shown that if the detonation wave has velocity higher than 2100 m/s at upstream of the model, detonation transmission will occur at downstream of the model.

Keywords: Flame Quenching, Detonation Wave, Porous Media

1. Introduction

Liquefied Petroleum Gas (LPG) in Indonesia is produced by Pertamina and it is usually used as fuel for industrial sector which needs combustion process in their production. Chemically, LPG produced by Pertamina consists of 30% propane and 70% butane. In order to increase combustion temperature and heat generation, usually oxygen is added to the combustion process. However, LPG and oxygen could react independently without air which results higher heat generation compared to LPG-air mixture reaction. High heat generation has high possibility to generate detonation wave when an accident occurs. Detonation wave is a reaction wave propagating with supersonic velocity and it could be generated from deflagration wave that keeps accelerating until reach supersonic velocity. In addition, detonation wave propagation is always accompanied by shock wave in front of reaction wave.

Detonation wave could be generated at an initial pressure of 20 kPa up to 100 kPa of LPG-oxygen mixture as observed by Sentanuhady et al. in 2013 [1]. They calculated that at 100 kPa of initial pressure, detonation wave could reach velocity up to 2320 m/s or 10.6 Mach numbers and peak pressure up to 2952,6 kPa or about 30 times of an initial pressure. Therefore, detonation wave propagating with high velocity and high pressure could harm people, environment, and piping system in industry. In order to mitigate detonation wave propagating by accident, there are several techniques to control detonation wave, such as mechanical method using perforated obstacle to quench detonation wave to be deflagration wave or chemical method. The technique to transform detonation wave to be deflagration wave is usually called as detonation quenching.

Experiments on characteristic of detonation propagation through orifice model have been carried out by researchers previously. Effect of geometry on the transmission of detonation through an orifice was observed by Liu et al. in 1984 using hydrogen-oxygen mixture diluted by nitrogen at room temperature [2]. They observed that the critical diameter for the detonation transmission through an orifice is identical to that for a straight tube and both follow the empirical correlation of $d_c \cong 13\lambda$. Later, Ciccarelli et al. in 1998 conducted experiment to observe detonation wave propagation through a single orifice plate in a circular tube using hydrogen-air mixture at an atmospheric initial pressure with

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Corresponding author: E-mail: jayan@ugm.ac.id

variation of initial temperature and hydrogen concentration [3]. They observed that critical diameter to transmit detonation is influenced by initial temperature elevation and hydrogen concentration of the mixture, thus the critical diameter of $d_c \cong 13\lambda$ stated by Liu before only applied for room temperature condition. Stoichiometric hydrogen-air mixture at initial temperature of 27 ^{o}C results to detonation failure because the number of cell inside the orifice is only 11 cells ($d_{orifice}$=11λ), which is smaller than the critical diameter value. However, for mixture with 24% of hydrogen at 377 ^{o}C of an initial temperature results transmission of detonation where is number cell inside the orifice about 14.3 ($d_{orifice}$=14.3 λ).

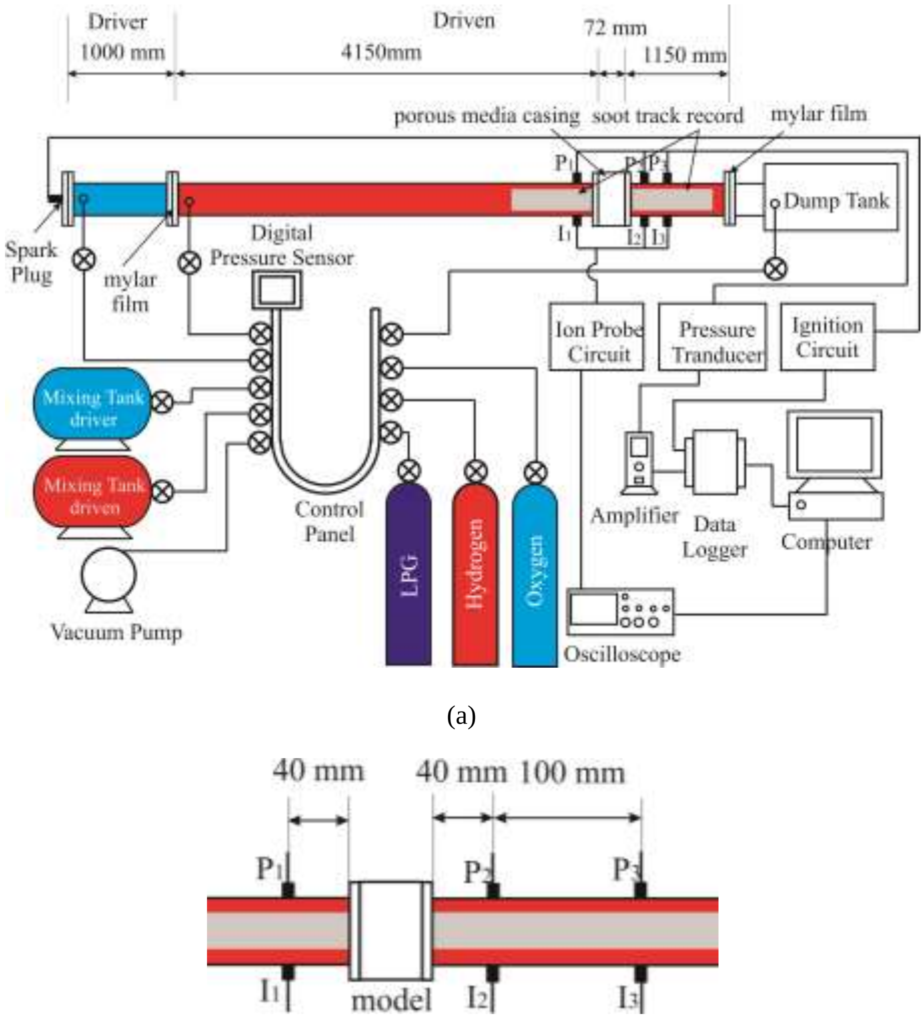
Characteristic of deflagration propagation passes through porous media was observed by Mihalik et al. in 1999 using methane and propane as fuel and air as oxidizer [4]. The experiment was carried out in a 1.8 m in length of transparent plexiglas tube of 5 cm of internal diameter with porous media model attached at distance of 0.9 m from the end of the tube. The porous media is composed of a packed bed of solid spheres supported on a wire screen. A range of materials with varying thermal conductivities are tested such as glass, stainless steel, and brass. They observed that flammability limit of the mixture pass through media porous is narrower than flammability limit of the mixture in pipe without model due to heat loss. Furthermore, they also observed that conductivity of the porous media does not influence the flammability limit directly, as they observed that flammability limit of methane-air mixture in packed bed of glass is 7,86% up to 10,87% while in packed bed of brass is 7,66% up to 10,96%.

Experiments of deflagration quenching using stainless steel porous media model inside Constant Volume Combustion Chamber were carried out by Sentanuhady et al. in 2011 [5]. They used LPG-air mixture at an initial pressure varied from 40 kPa up to 100 kPa and porous media with mass varied from 5 grams up to 20 grams. Their results showed that deflagration wave was always successfully quenched by porous media with each mass value at initial pressure about 40 up to 70 kPa, while gas mixture at initial pressure of 80 up to 100 kPa results deflagration wave reinitiated after quenching. They concluded that an initial pressure of the gas mixture and mass of the porous media significantly influence to the deflagration quenching. Related to porous media for flame quenching, in 2012, Ciccarelli stated that porous media has high surface area to volume ratio that enables to enhance heat transfer from flame front which is very important in flame quenching process. However, if the flame front is not quenched, the flow obstruction within the porous media can promote explosion escalation [6].

Results of previous researchs and experiments carried out by researchers indicates that an initial pressure of gas mixture, type of gas and its concentration, as well as mass of porous media which represent its porosity significantly influence the quenching process and possibility of reinitiation after quenching. The aim of this experiment is to observe characteristic of detonation wave propagating through stainless porous model and to analyze ability of porous media model to quench detonation based on variation of initial pressure by using stoichiometric LPG-oxygen mixture. The results of this experiment could be taken into consideration in designing and developing flame arrester for LPG combustion system.

2. Experimental Method

These experiments were conducted by using detonation test tube at Energy Conversion Laboratory of Mechanical and Industrial Engineering Department, Universitas Gadjah Mada. The detonation test tube was equipped by pressure sensors, ionization sensors, data acquisition system, and gas mixing system as shown in Figure 1(a). The detonation test tube which made from stainless steel material with inner diameter of 50 mm, consists of two sections, driver section of 1000 mm in length and driven section of 5000 mm in length. At the end of the detonation test tube, dump tank is attached in order to absorb reflected shock wave propagated to upstream direction. Each section of the tube is separated by 25 μm in thickness of mylar film to prevent mixing between driver gas and driven gas which contains different gas with different concentration and pressure.



(a)

(b)

Figure 1. (a) Schematic of experimental apparatus, (b) detail of sensor location in driven section

Stainless steel porous media model with constant mass of 10 gram was inserted in to a case which installed in the driven section in distance of 4000 mm from the start point of driven section. The case has perforated holes with 3 mm in diameter on its cross-sectional surface to enable the combustion wave to propagate through it. Details of case dimension of the porous media model is shown in Table 1 and Figure 2.

Three piezoelectric type pressure sensors made by PCB with 113A24 series were installed in the detonation test tube to detect pressure wave generated by reaction wave. The first sensor named sensor 1 was installed at upstream of the model while second sensor named sensor 2 and third sensor named sensor 3 were installed at downstream of the model. Three ionization sensors also were installed opposite to the pressure sensors to detect an arrival time of flame front propagation along the driven section. Detail of sensor position and distance between sensors are shown in Figure 1 (b). Aluminum plate coated by kerosene soot called as sooted track record was inserted at upstream and downstream of model to visualize the detonation cell that represents reaction rate of detonation propagation.

Driver section was filled with stoichiometric hydrogen-oxygen at constant initial pressure of 100 kPa which functioned as detonation direct initiator for mixture in the driven section. Furthermore, driven section was filled with stoichiometric LPG-oxygen at an initial pressure varied from 10 kPa up to 100 kPa with interval of 10. Each driven gas mixture was premixed inside mixing tank minimum 12 hours before used to ensure its homogeneity. Details of experimental condition are listed in Table 2.

(a) (b)

Figure 2. Porous media casing (a) computer design, (b) real model

Table 1. Dimension of media porous model

Parameter	Condition
Outer diameter of casing (mm)	135
Length of casing (mm)	72
Inner diameter of casing (mm)	52,5
Hole depth of casing (mm)	41
Material of casing	Steel
Material of media porous	Stainless Steel
Mass of porous media (gram)	10

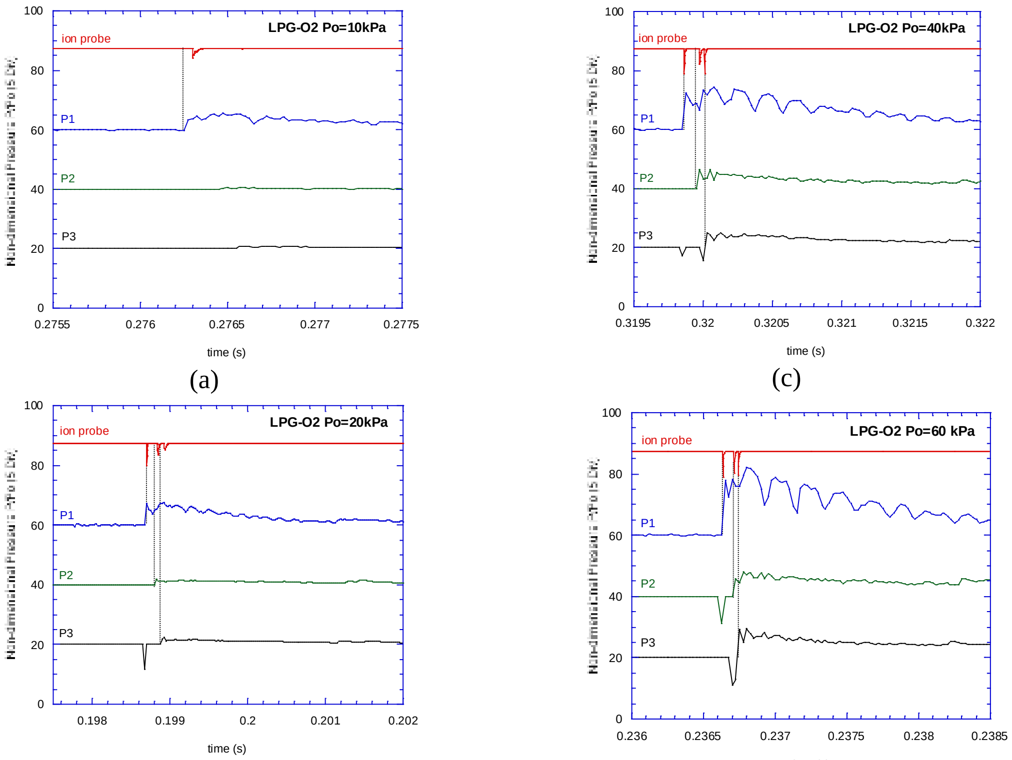
Table 2. Experimental conditions

Parameter	**Driver**	**Driven**
Fuel	Hydrogen	LPG Pertamina
Oxydizer	Oxygen	Oxygen
Equivalence Ratio	1	1
Initial Pressure (kPa)	100	10-100, interval 10
Initial Temperature	Room Temperature	Room Temperature
Mixing Method	Premixed	Premixed

3. Result and Discussion

Four mechanisms of combustion wave propagation were observed in the downstream of porous media, which are (1) deflagration quenching, (2) detonation quenching, (3) detonation reinitiation, and (4) detonation transmission.

Figure 3(a) shows data of pressure and ionization sensors at an initial pressure of 10 kPa and stoichiometric condition. Vertical axis is non-dimensional pressure and horizontal axis is time arrival flame front and shockwave. Histories of pressure are indicated as P1, P2, and P3, while history of time arrival of flame front is written as ion probe. Figure 3(a) indicates that pressure wave propagated at upstream of the model as shown by rise of the pressure about 50 kPa to the downstream direction. Flame front was also detected at this region as decrease of ion probe signal behind the pressure wave. Thus, it could be concluded that deflagration wave occurred at upstream of the model. The pressure wave and the flame front then would pass through into the model, and it will lose heat as well as momentum inside the model. The energy remaining in the combustion wave will decrease and it will not able to self-sustain propagation. As results, combustion wave will be quenched totally as shown as no pressure wave and ion probe signal at the downstream of the model. Furthermore, sooted track record attached at upstream and downstream of the model which is shown in Figure 4(a) indicates no detonation cell appeared at upstream and downstream of the model, thus it proves that detonation did not occur at an initial pressure of 10 kPa. This kind of phenomenon is referred as deflagration quenching or flame quenching phenomena.



(a)

(c)

(b)

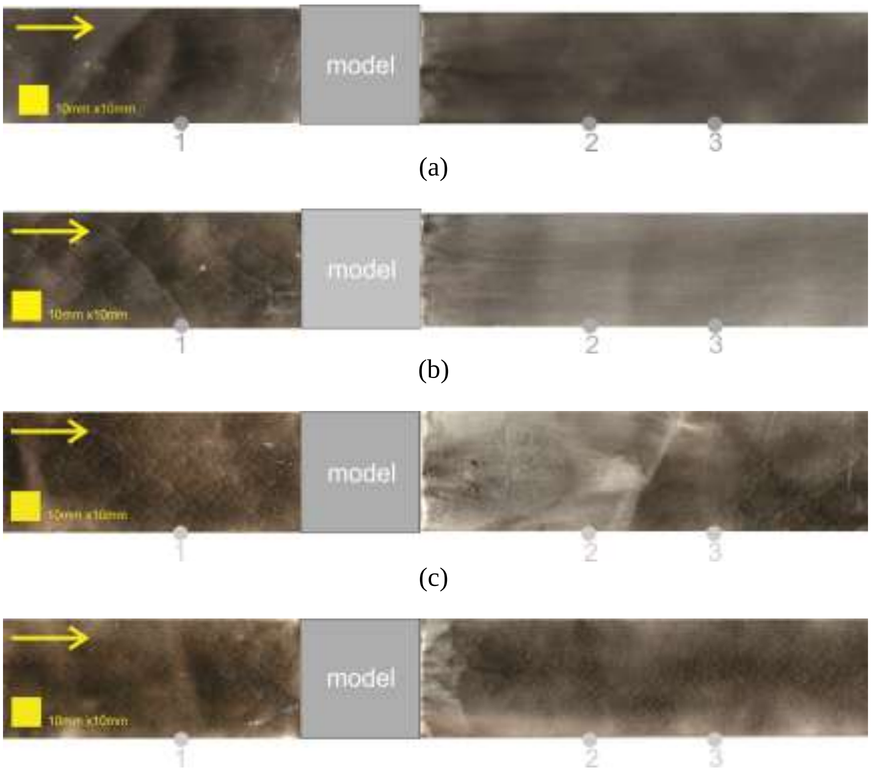
(d)

Figure 3. Data from pressure and ionization sensors (a) deflagration quenching, Po=10kPa (b) detonation quenching, Po=20kPa (c) detonation reinitiation, Po=40kPa (d) detonation transmission, at Po=60kPa.

By increasing the initial pressure to be 20 kPa, different phenomenon from deflagration quenching phenomena written above will be observed. In this condition, at the upstream region, detonation wave was occurred as shown in Figure 3(b) which represents result of the condition at initial pressure of 20 kPa. From the figure, it is observed that flame front and shock wave are detected by all sensors both at upstream region and downstream region. At this condition, detonation velocity could reach 1295 m/s as observed from previous experiment without model attached. The existence of detonation wave at upstream region of the model also exposed on the surface of sooted track record installed at the upstream of the model as shown in Figure 4(b).

Detonation wave propagated at upstream of the model will pass through into the porous media model and it will lose momentum and heat due to availability of porous media. Heat and momentum loss will cause the reaction rate decrease and as a result, the detonation wave will transform to deflagration wave as shown in Figure 3(b). The sooted track record attached at downstream of model which is shown in figure 4(b) indicates that the condition is deflagration wave as no detonation cell appeared on the surface of sooted track record. At downstream region, deflagration wave propagated with velocity of 678 m/s which is lower than theoretic CJ velocity of 2623 m/s. Maximum pressure of shock wave recorded at downstream was 50 kPa which is lower than theoretic CJ pressure of 1093 kPa. Due to the much lower flame front velocity and pressure wave resulted compared to theoretic CJ velocity and pressure of detonation wave, this condition should be deflagration wave.

Increasing of initial pressure higher than 20 kPa will results different phenomenon from condition with initial pressure 20 kPa or lower. Figure 3(c) shows condition of pressure and ionization histories from combustion condition at an initial pressure of 40 kPa. According to pressure sensor and ion probe result at upstream of the model, it are shown that pressure signal increase at same time as decreasing of ion signal, therefore this condition indicates that shock wave and flame front propagate concurrently as coupling. Thus, detonation wave was propagated at the upstream of the model which is proven by appearance of detonation cell on the surface of the sooted coated track attached at upstream of model.



(a)

(b)

(c)

(d)

Figure 4. Detonation cell visualization on sooted track record, (a) deflagration quenching, Po=10kPa (b) detonation quenching, Po=20kPa (c) detonation reinitiation, Po=40kPa (d) detonation transmission, Po=60kPa.

From previous experiment without model attached at same initial pressure, the velocity of flame front recorded was 1928 m/s, which is slightly lower than theoretical CJ velocity 2656 m/s. Even though it is slightly different between actual velocity and theoretical velocity, detonation wave propagated at the upstream was stable detonation as shown as uniform detonation cell appears on upstream sooted track record. Stable detonation propagated at upstream would pass through the model and lose heat and momentum due to porous media inside the model, thus detonation wave would be quenched as deflagration wave when emerge from the model. In this condition, reaction rate will decrease to be below of supersonic velocity caused by heat loss on the flame front. Although velocity of flame front has been decreased below sonic velocity, pressure wave in front of flame front could propagate at velocity higher than sonic as unstable shock wave. This condition is shown by Figure 3(c), where the flame front and pressure wave propagate separately. However, after the unstable shock wave passed over sensor 2, the shock wave interacted with surface of wall and would generate hot spot on the region around the wall. The hot spot will reinitiate detonation wave with very high reaction rate as shown on the sooted track record as very fine detonation cell. Reinitiated unstable detonation wave will propagated to downstream direction and will transform as stable detonation after few moments. This condition is shown by pressure sensor 3 and ion probe 3 which reacting at the same time in Figure 3(c), and also shown by detonation cell generated by reinitiated detonation wave. Detonation cell generated by reinitiated detonation wave appeared as very fine cell and would increase in size along the downstream of the sensor 3 as shown in Figure 4(c). Flame front propagation velocity measured between sensor 2 and sensor 3 was recorded as 1605 m/s which is much lower that theoretic CJ velocity 2656 m/s. This flame front propagation velocity is average velocity of deflagration and detonation condition, because reinitiation was started between sensor 2 and sensor 3. Before reinitiation, the condition is deflagration and the velocity should be subsonic, however after reinitiation, velocity of detonation wave propagation should be supersonic. The average velocity of the detonation of 1605 m/s is reasonable value which is calculated from two conditions, deflagration and detonation. Maximum shock wave pressure recorded at downstream was 254 kPa or about 6.4 times its an initial pressure which is lower than theoretic CJ pressure of 2230 kPa. This kind of phenomena also observed at initial pressure of 30 up to 50 kPa.

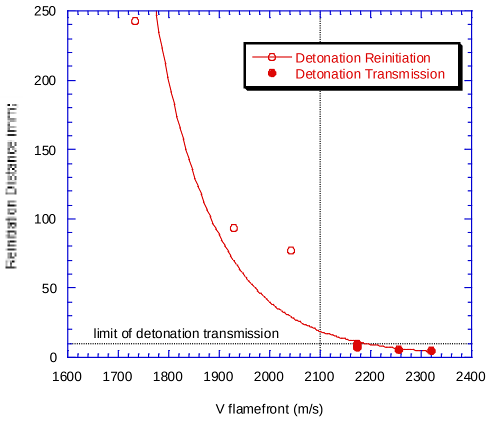


Figure 5. Relation between upstream flame front propagation velocity and reinitiation distance

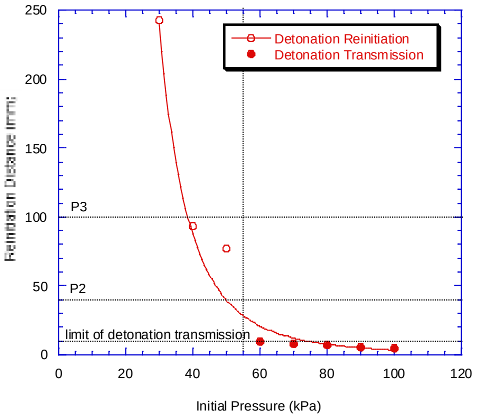


Figure 6. Relation between reinitiation distance of detonation and initial pressure value

Furthermore, increasing an initial pressure of the mixture to 60 kPa results detonation transmission whose pressure and ionization histories are shown in Figure 3(d). From Figure 3(d), it observed that shock wave reacted at the same time as the reaction wave at position of sensor 1, thus it can be concluded that detonation propagated at the upstream of the model. From previous experiment conducted without model and at same condition, it is shown that the velocity of flame front and the pressure of shock wave were 2173 m/s and 1113 kPa respectively. Thus, the condition at upstream region can be concluded that stable detonation propagated at upstream of the model. The stable detonation wave would propagate through into the porous media model and would lose heat and momentum, however, the amount of heat and momentum loss was too small compared to the energy of the detonation wave which already propagated with high velocity and pressure at upstream. Later on, detonation wave will be transmitted directly at downstream of the porous media model and continue to propagate without failure. This condition is shown as both at sensor 2 and sensor 3 positions, the pressure sensor and ion probe were reacting at the same time, thus it proved that detonation wave was propagated at both location. Furthermore, sooted track record shown in Figure 4(d) indicates that detonation cells are appeared directly after detonation wave passed through the model in distance of 10 mm from the model. Therefore, the detonation wave was transmitted directly after propagated through the porous media without decay to deflagration wave condition. Propagation velocity of flame front and pressure of shock wave at downstream were recorded as 2179 m/s and 597 kPa respectively, which are lower than CJ velocity of 2675 m/s and CJ pressure of 3400 kPa. Thus, it could be concluded that detonation transmission occurred at downstream of the model.

Relation between upstream flame front propagation velocity and reinitiation distance is shown in Figure 5. Vertical axis is distance of detonation reinitiation which is measured from the model while horizontal axis is the velocity of flame front propagation at upstream of the model. Figure 5 shows that combustion wave propagated with high velocity at upstream of the model will be transmitted directly while for combustion wave propagated with low velocity will be quenched or transmitted, the limit between the region could be about 2100 m/s. If the velocity of upstream region higher than 2100 m/s, the condition would be detonation transmission while if the velocity of upstream region lower than 2100 m/s, the condition would be detonation quenching or detonation reinitiation.

Reinitiation distance is indirectly influenced by initial pressure as shown in Figure 6. Vertical axis is distance of detonation reinitiation which is measured from the model while horizontal axis is the initial pressure of the LPG-oxygen mixture. Sensor 2 and sensor 3 is located at distance 40 mm and 100 mm respectively which are shown by dashed lines indicated by P1 and P2 symbol respectively. From the figure, it is shown that as the initial pressure increase, the reinitiation distance become shorter even at the initial pressure start higher than 50 kPa the detonation was transmitted directly. When the initial pressure is lower than 30 kPa, the pressure wave-wall interaction could not reinitiate detonation due to low reactivity of the mixture.

Since an initial pressure of the mixture directly influences a reaction wave propagation velocity, thus it will also affect to velocity of the pressure wave emerging from the model. High initial pressure will increase pressure wave emerged from the model and will increase possibility to reinitiate or transmit detonation wave.

4. Conclusion

The characteristics of combustion condition at the downstream of the stainless steel porous media model for LPG-oxygen mixture have been observed. Four phenomena of combustion at downstream of the model could be identified, which are deflagration quenching, detonation quenching, detonation reinitiation, and detonation transmission. The combustion condition at downstream is influenced by initial pressure of the mixture. At low initial pressure up to 10 kPa, only deflagration wave propagated at the upstream and will be quenched at the downstream of the model. Increasing the initial pressure to 20 kPa at the upstream of the model, detonation wave will be generated at upstream of the model but it will decay to deflagration wave at the downstream. At initial pressure of the mixture of 30 kPa up to 50 kPa, detonation wave was generated at upstream of the model which then will decay after emerged from the model to be deflagration wave, however, strong shock wave propagates to downstream and will interact with surface of wall and produce hot spot near the surface of wall. The hot spot will reinitiate the detonation wave as unstable detonation wave appeared as very fine cell close to location of shock wave-wall interaction. Further increasing the initial pressure of the mixture higher than 50 kPa will produce stable detonation wave at upstream of the model and directly transmitted to detonation wave without failure at the downstream of the model. By observing the propagation velocity of the flame front at upstream, there is a limit value of 2100 m/s for flame front propagation velocity which will cause detonation reinitiation or detonation transmission. If the flame front propagates with velocity higher than 2100 m/s at upstream of model, the detonation will be transmitted directly at downstream of model with 10 gram stainless steel porous media.

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