The Characteristics of LPG Detonation Wave Propagation Behind Porous Media Model

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Abstract. LPG-air mixture enriched with oxygen is usually used for generating heat in industry sector. However, it is possible 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 present study aims to investigate the characteristics of the detonation wave after propagating through the porous media model. The experiments used a detonation test tube with 50 mm of inner diameter and 6 m of total length. The test tube consists of two sections, 1 m long driver section and 5 m long driven section. The driver section and driven section are separated by Mylar film to prevent mixing between driver gas and driven gas, which consists of different gas mixture with different pressure. The driver section contained a stoichiometric H2-O2 mixture at constant initial pressure, which function as a direct initiator for detonation in the driven section. Besides, the driven section contained a stoichiometric mixture of LPG-oxygen and LPG-air at the initial pressure varied from 20 kPa to 100 kPa with an interval of 10 kPa. The stainless-steel porous media with masses of 15 g and 20 g were inserted in a cylindrical case which had been perforated with small holes on its cross-sectional surface to enable detonation wave to propagate through it. The observation of detonation wave propagation was conducted at upstream and downstream of the model. Two mechanisms of detonation wave propagation were observed in the downstream of the porous media model for combustion of the LPG-oxygen mixture; they are detonation re-initiation and detonation transmission. However, the LPG-air mixture could not generate a detonation wave. Additionally, the 5 g increments of the stainless-steel porous media mass only significantly increase the re-initiation distance of detonation (Dri) for mixture with low initial pressure, 20 kPa up to 50 kPa and did not significantly influence re-initiation distance of detonation for mixture with a high initial pressure of 60 kPa to 100 kPa.

1. Introduction
Liquefied Petroleum Gas (LPG) is one of the most used fuels in Indonesia both for household and industrial needs. It is commonly used during the last decades for reducing oil usage as a primary energy source to balance the Indonesia national best energy mix [16]. LPG is usually burned by using air as an oxidizer for household needs. On the other hand, oxygen is usually added to LPG-air combustion process to increase energy generation and flame temperature for industrial needs [22].

Detonation wave is defined as a reactive shockwave that propagates close to an ideal Chapman-Jouguet (CJ) velocity and followed by a chemical reaction [12]. As the results, the air and fuel mixture are compressed and ignited by the shockwave, resulting in an energy release that in turn, supports the
shockwave propagation [15]. Research conducted by Febryanto showed that the detonation wave could be generated from an LPG-air mixture with a concentration of 6% LPG and LPG-oxygen mixture with a concentration of 3% to 33% LPG [9]. Moreover, the detonation wave could be generated from a stoichiometric LPG-oxygen mixture with an initial pressure of 20 kPa to 100 kPa as reported by Sentanuhady [22]. The research showed that LPG-oxygen detonation waves could propagate with velocity up to 2320 m/s and pressure of shockwave up to 2952.6 kPa.

In practical, these high velocity and pressure possessed by detonation waves could harm people and the environment in the surroundings of the LPG combustion system if an accident occurs. Some major accidents caused by explosion induced by high-reactivity LPG or methane combustion during the storage and transportation system were noted, with more than 3000 gas explosion accidents that occurred in China [3,13,23]. LPG has odor-less, high-flammability, and very low boiling point characteristics. When LPG is released to the atmosphere, a vapor cloud will be formed in a subsequent fire and explosion if an ignition source exists [23]. Therefore, the mitigation of detonation waves is very important to ensure safety in the LPG combustion system [11,21]. Hence, the understanding of detonation wave propagation during the detonation mitigation is essential.

Detonation mitigation, also known as detonation quenching, can be defined as the transformation of detonation wave to less harmful deflagration wave. In this process, the flame front still could propagate, but in much lower subsonic velocity. Detonation quenching can be performed by using either chemical or mechanical methods. An example of chemical methods is by injecting a flame suppressant into the combustion pipe. On the other hand, mechanical methods can be achieved by inserting a flow obstacle in the combustion pipe.

Various attempts of detonation quenching using the mechanical method have been previously observed by the previous scholars, such as research on detonation quenching using orifice model [4,19]. They observed that there are 3 mechanisms of detonation propagation that occur in the downstream of the orifice model: detonation failure, detonation re-initiation, and detonation transmission. Nevertheless, this method is not effective because detonation still could reinitiate in the downstream of the model. Moreover, a convergent-divergent nozzle was used by Hayashi [10]. They observed that the supersonic detonation wave accelerated as they propagated through the convergent section of the nozzle. However, it decelerated as they propagated through the divergent section of the nozzle, which results in the subsonic deflagration wave. In addition, a narrow gap was also used by Sentanuhady for detonation quenching [20]. The detonation wave was diffracted while it propagated through the narrow gap model and transformed to deflagration [20]. Nevertheless, the detonation wave could still reinitiate in the downstream of the model. There were two mechanism of detonation re-initiation observed from this research: detonation re-initiation due to interaction between the shockwave and the pipe wall, and due to the Detonation to Deflagration Transition (DDT) process.

Besides, there is another promising method using the porous media model. A porous media has a high surface area to volume ratio, so it logically can absorb more heat from the flame front which propagates through it; thus, it would affect the propagation of the flame front. In deflagration propagation, Mihalik conducted that the flammability limit of the mixture through porous media is narrower than the flammability limit of the same mixtures in the pipe without porous media which is caused by heat loss occurred from the flame front to the porous media [14]. A numerical simulation study conducted by Di Mare also showed a good agreement to support the statement [7]. Moreover, porous media is able to extract thermal energy from the flame, and the reduction of gas temperature leads to quenching [5].

An essential work on the transition of flame propagation inside a square cross-section channel containing aluminum oxide spherical bead-porous media using hydrogen-air mixture at various initial pressures has been investigated by Ciccarelli [5]. They observed the process of flame propagation through porous media, starting from the formation of the parabolic flame front to the formation of the planar flame front [5]. Additionally, this research also showed the Detonation to Deflagration Transition (DDT) through porous media.
Among the researchers, Sentanuhady have observed propagation of LPG-air deflagration wave through stainless steel porous media model using the Constant Volume Combustion Chamber (CVCC) with the mixture at various initial pressures and with various porous media masses [21]. The research showed that for some value of initial pressure and porous media mass, the deflagration wave was successfully quenched [21]. Meanwhile, Ciccarelli stated that porous media have a high surface area to volume ratio that is needed for flame quenching process. But if the flame was not quenched, the flow obstruction in the porous media could promote explosion escalation [6].

In the present work, LPG detonation transmission and re-initiation using a porous media model with two values of mass were studied. A stainless-steel porous media model was used due to a consideration of high thermal conductivity and abundant availability. Furthermore, initial pressures of the mixtures are varied from 20 kPa to 100 kPa, while the initial temperature is set constantly at room temperature, about 25°C. The detonation wave would propagate through the porous media model, meanwhile, the condition in the upstream and downstream of the model were also recorded.

2. Experimental Apparatus and Procedure

These experiments were conducted at Detonation Test Facility of Energy Conversion Laboratory, Universitas Gadjah Mada. This facility consists of a horizontal circular cross-section Detonation Test Tube (DTT) with a diameter of 50 mm and a total length of 6 m. A schematic diagram of the experimental apparatus is shown in Figure 1. The test tube consists of two sections, 1 m in length driver section and 5 m in length driven section. It is also featured with a dump tank to absorb the reflected shocks. The sections are separated by Mylar film with a thickness of 50 μm to prevent mixing between gasses of each section. A spark plug was installed at the upper end of the driver section to ignite the combustion inside the tube. The porous media model was inserted in the driven section at position 5 m from the spark plug.

Figure 1. A schematic diagram of the experimental apparatus

The detonation test tube was equipped with four PCB Piezotronics pressure sensors and 4 ionization probes to detect the pressure of shockwave and time arrival of the flame front inside the tube, respectively. Two of the pressure sensors were located in the upstream of the model while the two others were located in the downstream. On the other hand, each of the ionization probe was installed in the opposite of the pressure sensor. Data from every sensor and probe were displayed and recorded by the digital oscilloscopes. The soot track records were inserted in the upstream and downstream of the model to visualize the detonation cells. There are 3 different types of mixtures used
in these experiments, hydrogen-oxygen mixture, LPG-oxygen mixture, and LPG-air mixture. The driver section was filled by a stoichiometric hydrogen-oxygen mixture at a constant initial pressure of 100 kPa and room temperature, 25°C. On the other hand, the driven section used LPG as the fuel and two types of gas as the oxidizer: air and oxygen. Initial pressures of the mixture inside the driven tube were varied from 20 kPa up to 100 kPa with an interval of 10 kPa. Both LPG-air and LPG-oxygen mixture were set at the stoichiometric concentration. All mixtures were premixed inside mixing tanks at least 12 hours to ensure the homogeneity. The filling of DTT and gas mixing processes were controlled by a high precision digital pressure sensor. The details of the experimental condition are listed in Table 1.

Table 1. Experimental conditions

| Parameter                  | Driver          | Driven          |
|----------------------------|-----------------|-----------------|
| Fuel                       | Hydrogen        | LPG             |
| Oxidizer                   | Oxygen          | Oxygen, air     |
| Equivalence Ratio          | 1               | 1               |
| Initial Pressure (kPa)     | 100             | 20-100, interval 10 |
| Temperature (° C)          | 25              | 25              |
| Mixing method              | Premixed        | Premixed        |
| Mass of Porous Media (g)   | 15 and 20       |                 |

Specifically, the LPG produced by Pertamina consists of 35% C₃H₈ and 65% C₄H₁₀. An ethanethiol was added to LPG to give scent to odorless propane, butane, and isobutane mixture to indicate the leakage. The test specifications of Pertamina LPG are stated in Table 2.

Table 2. Test specification of Pertamina LPG

| TEST                      | MIN     | MAX     | METHOD             |
|---------------------------|---------|---------|--------------------|
| Specific gravity at 60/60°F| To be reported | 120 | ASTM D-1657        |
| Vapor pressure 100°F, psig| -       | 120     | ASTM D-1267        |
| Weathering test 36°F, % vol| 95      | -       | ASTM D-1837        |
| Copper corrosion 1 hr, 100°F| -      | No. 1   | ASTM D-1838        |
| Total sulfur, grains/100 cu-ft| -      | 15      | ASTM D-2784        |
| Water content             | No free water | Visual |                    |

Composition:

|                   | % vol | % vol | % vol |
|-------------------|-------|-------|-------|
| C₂                |       | -     | 0.2   |
| C₃ + C₄           |       | 97.5  | -     |
| C₅ + (C₅ and heavier) |       | -     | 2.0   |
| Ethyl or Butyl Mercaptan added | mL/1000 AG | - | 50    |

Source: Directorate General of Oil and Gas of Republic Indonesia Decree no: 25K/36/DDJM/1990

The porous media casing was made of stainless steel with a circular cross-section, with dimension: 135 mm of outer diameter and 72 mm length. The casing has a hollow space inside of it with 52.5 mm diameter and 41 mm depth, thus providing 88709.9 mm³ or 88.7 ml volume of the cavity. Both sides of cross-sections of the casing had been perforated with small holes, of which diameter is 3 mm, to enable combustion wave to propagate through the casing. The casing was useful as a place to insert the porous media, as shown in Figure 2 (a) and (b). This research used stainless steel porous media, shown in Figure 3, with a mass variation of 15 g and 20 g based on previous research by Sentanuhady that proved these values of mass are enough to quenched deflagration [21]. The detailed properties of porous media are expressed in Table 3.
Figure 2. (a) Casing of porous media, (b) casing of porous media with lid opened

Figure 3. (a) Dimension of fiber composing the porous media model, (b) curled fiber composing of porous media, (c) porous media

Table 3. Properties of porous media

| Parameter                  | Values          |
|----------------------------|-----------------|
| Density (kg/m³)            | 3700            |
| Material                   | Stainless steel |
| Mass (g)                   | 15              |
| Mass (g)                   | 20              |
| Volume based porosity      | 0.95            |
| Surface area (m²)          | 0.256           |
| Volume based porosity      | 0.94            |
| Surface area (m²)          | 0.341           |

Prior to the experiments, the properties of porous media were measured to ensure uniformity of its properties. A bundle of porous media was weighed using electric scales to find its mass and its volume was measured using the water displacement method. Hence, the density of the porous media could be calculated. Then, volume-based porosity and surface area of the porous media were calculated.

Porosity represents the void fraction of a matter which denotes the ratio between the total volume of void ($V_v$) and total volume of void-solid ($V_T$).

$$\phi = \frac{V_v}{V_T}$$  \hspace{1cm} (1)

In this research, the volume-based porosity was calculated by dividing the difference between the volume of hollow space of the porous media casing and the volume of porous media with the volume of the hollow space of the porous media casing.

$$\phi = \frac{V_{casing} - V_{porous\ media}}{V_{casing}}$$  \hspace{1cm} (2)

Moreover, as the porous media consists of curled filaments, the thickness and the width of the filament could be measured. By knowing the volume of a bundle of porous media, the thickness and...
width of the filament, the total length of the filament-forming the porous media can be calculated. Furthermore, the total surface area of the filament-forming the porous media can also be calculated. The calculated porosity and surface area of the porous media used in this research are listed in Table 3.

3. Results and Discussions

In the present work, a stoichiometric mixture of hydrogen and air was reacted in a constant initial pressure of 20 kPa at the driver section while two stoichiometric mixture types of LPG-air and LPG-oxygen with various initial pressures were reacted and evaluated at the driven section. The analysis of the combustion phenomena for each mixture is presented below.

3.1. LPG-air mixture

When LPG and air were simultaneously mixed and ignited, there was no detonation generated from the combustion of the stoichiometric LPG-air mixture in DTT without porous media. The deflagration was observed instead of detonation from the mixture with high initial pressure and no combustion observed from mixture with low initial pressure. Theoretically, deflagration is a combustion whose flame front propagates in subsonic speed. In the present study, deflagration of the LPG-air mixture was observed from mixture at an initial pressure of 60 kPa to 100 kPa. An example of pressure and flame propagation results from the LPG and air combustion at an initial pressure of 100 kPa is displayed in Figure 4.

![Figure 4](image)

**Figure 4.** Data from pressure sensors and ionization probes of LPG-air deflagration from mixture at an initial pressure of 100 kPa.

This figure indicates that the flame front is always detected with time lag behind the shockwave detection at every location of the sensor. It means that deflagration occurred at every location of the sensor. Furthermore, the flame front detection at most of the sensor locations is very weak, as shown by a small decrease of ionization signal from the 2nd, 3rd, and 4th sensors. The actual velocity of flame front propagation calculated from the data is 906 m/s and the mean of actual shockwave pressure is 3907 kPa while the theoretical CJ velocity is 1823 m/s and the theoretical CJ pressure is 1886.18 kPa. The soot track record from this experiment is presented in Figure 5 and it shows no formed detonation cell.
Figure 5. Soot track record of deflagration of LPG-air mixture at an initial pressure of 100 kPa located in distance 4 m to 4.28 m from the start point of the driven section.

Deflagration generated from the mixture at initial pressure lower than 100 kPa was observed to be very weak. It is indicated by a very small decrease in the ionization signal and the flame front. Also, detections of the ionization signal by each sensor area coincide. Therefore, the actual flame front velocity could not be measured. An actual pressure of shockwave from LPG-air combustion was very high, yet it could not generate detonation and even the flame front generation was also very weak. The weak flame front of the LPG-air combustion was caused by a very little amount of LPG and oxygen content in the stoichiometric LPG-air mixture (only about 3.4% LPG and 20.3% oxygen). Otherwise, the rest percentage of the LPG-air mixture contained nitrogen that acts as diluent. The heat generated by the combustion process was absorbed by nitrogen that is possible to increase the temperature of nitrogen. Moreover, the small percentage of LPG, propane, and butane, in the mixture induced the fuel to be difficult to react with oxidizer to perform a combustion reaction.

3.2. LPG-oxygen mixture

The combustion of the LPG-air mixture only generated deflagration wave instead of detonation wave, while the LPG-oxygen mixture with initial pressures of 20 kPa to 100 kPa could generate detonation waves. Therefore, only the LPG-oxygen mixture becomes a focus in this present work. Here, there are two mechanisms of detonation propagation observed in the downstream of the porous media model: (a) detonation re-initiation, and (b) detonation transmission.

3.2.1. Detonation re-initiation

The first mechanism was the detonation re-initiation, defined as a condition when the detonation wave was quenched after passing through the model, but the detonation wave was able to reinitiate far downstream of the model. This mechanism was observed from the combustion of the hydrogen-oxygen mixture at an initial pressure of 20 kPa with a porous media mass of 15 g. Data from pressure sensors and ionization probes of this condition is shown by Figure 6 (a). The vertical axis corresponds to non-dimensional pressure $P/P_o$, while the horizontal axis corresponds to time. Time arrival and pressure of shockwave are indicated by the rise of $P_1$, $P_2$, $P_3$, and $P_4$ signal whereas time arrival of the flame front is indicated by the decrease of the ion probe signal.

It is also indicated that in the upstream of the porous media model, the flame front was detected by ionization probe 1 and 2, at the same time with the shockwave detection by the pressure sensor 1 and 2. On the other hand, the flame front was detected in downstream of the model with some time lag behind the detection of the pressure wave. Hence, the detonation occurred in the upstream of the model while deflagration occurred in the downstream of the model. Calculation of data from pressure sensors and ionization sensors gives actual downstream flame front velocity and shockwave pressure of 626 m/s and 295.86 kPa respectively in downstream of the model which are much lower than theoretical CJ velocity and pressure 2322 m/s and 726.02 kPa.

The soot track record inserted in the downstream area is shown in Figure 7 (a). Detonation cells started to form a distance of 320 mm behind the model, which was far behind the location of the sensors. However, in this location of detonation re-initiation, there was no sensor installed, thus the pressure of shockwave and the velocity of flame front propagation and shockwave propagation of the reinitiating detonation could not be calculated. To summarize, the detonation propagated in the...
upstream of the model was successfully quenched after passing through the model; however, it was able to re-initiate at 320 mm behind the model.

![Graphs of pressure sensors and ionization probes](image)

**Figure 6.** Data from pressure sensors and ionization probes of condition (a) detonation re-initiation, from mixture at $P_i = 20$ kPa and $m_{porous} = 15$ g, and (b) detonation transmission, from mixture at $P_i = 80$ kPa and $m_{porous} = 20$ g

![Visualizations](image)

**Figure 7.** Visualization of detonation cell in soot track record in the downstream of the model for condition (a) detonation re-initiation, at $P_i=20$ kPa and $m_{porous}=15$ g, (b) detonation transmission, at $P_i=80$ kPa and $m_{porous}=20$ g
3.2.2. Detonation transmission

The second mechanism is detonation transmission, defined as a condition when the detonation waves were transmitted directly after passing through the porous media model. The example of pressure and flame propagation history of the detonation transmission phenomenon is displayed in Figure 6 (b) which shows data from the combustion of the mixture with an initial pressure of 80 kPa using 20 grams of porous media. It is shown from the figure that at every location of sensors, the flame front was detected at the same time with the detection of the shockwave. This indicates that detonation occurred at every location of the sensors, in the upstream and downstream of the model. Calculation of data from pressure sensors and ionization sensors gives the actual velocity of the flame front and pressure of shockwave 2259 m/s and 3086 kPa respectively in downstream of the model. These values are almost reaching the theoretical CJ velocity of 2387 m/s and CJ pressure 3856 kPa.

The soot track record of this experiment is displayed in Figure 7 (b). It shows that in the downstream of the porous media model, the detonation cell started to appear at a distance of 18 mm from the model which indicates the detonation was generated immediately behind the model. Therefore, the detonation propagates in the upstream of the model is directly transmitted after passing through the model. When flame front propagates in supersonic velocity which approaches the shockwave propagation velocity, it can be taken as the actual detonation wave propagation velocity. On the other hand, the actual flame front velocity can be calculated from ionization probe data, by dividing the distance between sensor location with the time interval between detections of the flame front by each sensor. The theoretical value of detonation wave velocity is the CJ velocity which can be calculated from the initial condition of the mixture.

Figure 8 (a) displays the relationship between actual flame front velocity and theoretical CJ velocity to the initial pressure of the mixture. Close observation of the figure indicates that the actual flame front propagation velocity for every initial pressure was slightly lower than the CJ velocity at the same initial pressure. This was caused by the assumption and simplification made in calculating the CJ theoretical velocity that CJ theory assumes the detonation wave as a one-dimensional planar wave without reaction zone. However, both of the actual upstream flame front velocity and theoretical CJ velocity increase as the initial pressure of the mixture increases since the mixture with higher initial pressure contain more energy that could generate flame front with higher kinetic energy [18].

At the low initial pressure, where 20 kPa and 30 kPa as the example, the downstream flame front velocity for every value of porous media mass is much lower than the upstream flame front velocity. This means that the porous media models successfully decelerate the velocity of the flame front while the flame front propagates through the porous media. However, at high initial pressure, the downstream flame front velocities are higher than the upstream flame front velocity. This was because after emerging from the model, the detonation wave still contains a large amount of energy while it undergoes turbulence as an effect of the flow obstruction within the porous media model. Furthermore, by comparing downstream flame front velocity behind porous media with masses of 15 g and 20 g, it is shown that at low initial pressure, the porous media with higher mass resulted in a lower downstream velocity even though the decrease was only in a small amount. However, as the initial pressure increases, the difference between the velocity behind the two values of porous media masses decreases.
Figure 8. (a) Graphic of flame front velocity and CJ velocity vs initial pressure of LPG-oxygen mixture (b) $D_{ri}/d$ vs initial pressure

Figure 8(b) addresses the relation between the non-dimensional detonation re-initiation distance ($D_{ri}$) to the pipe diameter ($d$) ratio with the initial pressure of the LPG-oxygen mixture. It is defined as the distance needed for detonation to successfully reinitiate in the downstream of the porous media model. The re-initiation distance was obtained by measuring the distance from porous media to location where the detonation cell started to appear in the soot track record in the downstream of the model. The vertical axis corresponds to the non-dimensional re-initiation distance to the pipe diameter ratio, whereas the horizontal axis corresponds to the initial pressure of the LPG-oxygen mixture. The vertical axis starts at 0 value which corresponds to the position of the model. The P3 denotes the position of sensor 3 which is at a distance of 40 mm from the model while the P4 denotes the position of sensor 4 which is at a distance of 100 mm from the model. This figure contains two curves, the solid curve shows the $D_{ri}/d$ for the porous media model with a mass of 15 g and the dashed curve shows $D_{ri}/d$ for the porous media model with a mass of 20 g.

Close observation of the figure illustrates that the detonation re-initiation distance is shorter as the initial pressure of the mixture increases. The initial pressures of the mixture directly influence the flame front propagation velocity; thus, it also affects the velocity of the pressure wave emerging from the model which corresponds to the energy transmitted by the flame in the downstream of the model. As the velocity of the flame front increase in the downstream of the model, the energy transmitted by the flame front after emerging from the model is increased; thus, the time needed for detonation to reinitiate become shorter, which means the re-initiation distance of detonation also becomes shorter.

In this research, regimes of detonation propagation behind porous media are classified based on the re-initiation distance of the detonation. The phenomenon in the downstream of the model is classified to be detonation re-initiation if the $D_{ri}$ is higher than 40 mm ($D_{ri}/D>0.8$) which is behind the location of sensor 3. On the other hand, the phenomenon in the downstream of the model is classified to be detonation transmission if the $D_{ri}$ is lower than 40 mm ($D_{ri}/D<0.8$) or at a location between sensor 3 and the model. The effect of the increase of porous media mass in the re-initiation distance of detonation is insignificant for mixture with high initial pressure. The differences of $D_{ri}$ for porous media with a mass of 15 g and 20 g are only small for mixture with an initial pressure of 50 kPa up to 100 kPa, which is only 2 mm in average. In contrast, the increment of $D_{ri}$ due to the increasing of porous media mass is significant for mixture with low initial pressure, 20 kPa up to 40 kPa. Even for mixture with an initial pressure of 20 kPa, the increment of $D_{ri}$ reaches the value of 205 mm.

When the LPG-oxygen detonation wave propagates through a porous media model, it undergoes heat and momentum losses. Heat loss from the detonation wave occurs due to heat transfer from the
flame front to the porous media and the porous media casing [8,6,1]. For instance, heat energy, owned by the flame front, could be transferred and absorbed to the porous media. Particularly, conduction in porous media depends on the matrix and thermal conductivity of each phase (solid and fluid) of the media where the heat capacity and contact resistance also play an important role. On the other hand, momentum loss occurs because the shockwave and flame front with very high velocity collide the porous media and the porous media casing. Consequently, the energy transmitted by the detonation wave decreases. Thus, it affects the mechanism of detonation propagation in the downstream of the model.

The first mechanism of detonation propagation behind the porous model was the detonation re-initiation, observed at the condition of stoichiometric LPG-oxygen mixture with low initial pressure. This condition generated detonation that contained only a small amount of energy, indicated by low propagation velocity and low shockwave pressure. When the detonation wave propagates through the porous media model, heat and momentum losses was higher than the energy possessed by the wave. As a result, the detonation wave could not propagate sustainably after emerging from the porous media and it was transformed into deflagration. Hence, the deflagration wave that emerged from the porous model only contained low energy; thus, more time was needed to transform it into the detonation wave again. This mechanism was observed at the condition of 15 g of porous media for mixture with an initial pressure of 20 kPa and 30 kPa and condition of 20 g of porous media for mixture with an initial pressure of 20 kPa to 40 kPa.

The second mechanism was the detonation transmission which was observed at the condition of stoichiometric LPG-oxygen mixture with high initial pressure. The mixture with high initial pressure generated detonation wave containing a large amount of energy, indicated by high detonation propagation velocity and high shockwave pressure. When the detonation wave propagated through the porous media, it suffered a small amount of heat and momentum loss rather than the possessed energy. Therefore, the detonation wave could maintain its propagation at the downstream area of the model. Meanwhile, in some cases, it was easily reinitiated immediately. This mechanism was observed at the condition of 5 g of porous media for mixture with an initial pressure of 40 kPa to 100 kPa and the condition of 20 g of porous media for mixture with an initial pressure of 50 kPa to 100 kPa.

From the viewpoint of detonation to deflagration transition (DDT), an effective heat transfer from the combustion zone to the porous bed is required. For the porous model, high surface area and the volume ratio of porous media become an essential factor to ensure the heat transfer effectiveness and efficiency. Therefore, a lot of heat from the flame front is absorbed by the porous bed, depends on the flame velocity [2]. The wave velocity determines the combustion regime and flame propagation mechanism. Furthermore, momentum transfer that occurs since the flame front collides the interior of porous media leads to an effective way of flame quenching phenomenon or detonation attenuation, as also explained by Radulescu and Maxwell by the presence of wave diffraction when the primary detonation wave collides the obstacles [17].

4. Conclusion
The characteristics of LPG detonation wave propagation mechanisms in the downstream of the stainless-steel porous media model were studied. The effect of porous media mass to the characteristics of LPG detonation wave propagation in the downstream of the model was also investigated. The LPG-air mixture only generates a deflagration wave instead of a detonation wave, while the LPG-oxygen mixture could generate a detonation wave. The observation on the characteristics of the LPG-oxygen detonation wave conducted in the downstream of the porous media model results in two different phenomena: (a) detonation re-initiation, and (b) detonation transmission.

Detonation re-initiation was recognized when the detonation wave was quenched after passing through the model, but was able to reinitiate far downstream of the model. It was indicated by the high value of the re-initiation distance of detonation in the downstream of the porous media model, $D_s > 40$ mm. This phenomenon was observed for mixture with an initial pressure of 20 kPa and 30 kPa (for 15
Detonation transmission was a mechanism when the detonation was transmitted directly after passing through the porous media model. It was indicated by the low value of the re-initiation distance of detonation in the downstream of the porous media model, $D_\text{ri}<40$ mm. This mechanism was observed for mixture with an initial pressure of 40 kPa to 100 kPa (for 15 g porous media), and for mixture with an initial pressure of 50 kPa to 100 kPa (for 20 g porous media). Under the increase of porous media mass (the addition of 5 g), the re-initiation distance of detonation ($D_\text{ri}$) behind the porous media model also increases. However, $D_\text{ri}$ significantly increases only for mixture with low initial pressure.

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