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Effect of Different Liquid Fuels on Impact Pressure of Supersonic Liquid Fuel Jets

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***Abstract*— This study is to measure the impact pressure of supersonic liquid fuel jets injected in quiescent air at various stand-off distances from the nozzle exit. The main focus is to investigate the effect of different liquid fuel jets on the impact pressure. In this study, the supersonic liquid fuel jets are generated by the impact of a projectile, which known as impact driven method, launched by a horizontal single-stage gas gun (HSSGG). The impact pressures of the jets were measured by the PVDF pressure sensor. Moreover, the impact pressures were calculated from the water-hammer equation in order to compare with the measurement. From comparison, the impact pressure of all jets calculated from the equation and the measurement were different. From the measurement, the impact pressures of all jets decrease as the stand-off distance increases. The maximum impact pressure of diesel, kerosene, gasoline and alcohol jets is 662.37, 606.60, 559.50 and 699.5 MPa, respectively. Besides, it was found that the density is significantly the physical property of jet-impact pressure. The surface tension and the kinematics viscosity are significantly the physical property for the trend of jet-impact pressure against the stand-off distance.**

***Keywords*— impact pressure, supersonic liquid fuel jets, impact driven method, PVDF pressure sensor, water-hammer equation**

I. Introduction

It is known well that the impact of high-speed liquid jet can cause damage or permanently deform of structure materials. If the high-speed jet strikes on solid surface, it can generate a great number of pressures on solid surface. This pressure causes stresses, which can create damage in material. Such damage can occur on the surface of aircraft during high-speed flight in rain, steam turbine blades, surface cleaning, fuel injection part, etc [1, 2]. Therefore, the study of high-speed liquid jet impact on surface has been interested in wide range of technology, such as jet cleaning and cutting technology, mining and tunneling [3-5].

In 1961, F.P. Bowden et al. [6] studied the deformation of solid by the impact of a water jet on the solid surface. It was found that there were five general types of deformation produced in the solid. There were: (i) circumferential surface fractures, (ii) subsurface flow and fractures, (iii) large-scale plastic deformation, (iv) shear deformation around the periphery the impact zone and (v) fracture due to the reflexion of stress wave. After that in 1966, J.H. Brunton [7] generated water jet at speed up to 1,200 m/s to investigate the mode of deformation in brittle and plastically deforming material. It was found that the predominating mechanism of deformation depended on mechanical properties of the solid and the impact velocity of jet.

From the previous literature reviews [1-7], the studies of high-speed liquid jet impact on a solid surface have been focused on the investigation of the damage out across the surface, the calculation of water-hammer pressure for 2-3 time speed of sound and the impact pressure measurement of water jet only.

In this study, therefore, the impact pressures of high-speed liquid fuel jets (diesel, kerosene, gasoline and alcohol jets) in supersonic range at various stand-off distances from nozzle exit were measured by the PVDF pressure sensor, which was specially designed and developed. The values of impact pressure obtained from the PVDF pressure sensor with that calculated from water-hammer equation were compared.

II. Experiments

A. *Jet Generation*

In this study, supersonic liquid fuel jets are generated by impact driven method [6, 7]. Using this technique, the liquid retained inside the nozzle cavity is impacted by a high-speed projectile. The liquid obtains the momentum transfer from the projectile and is injected from the nozzle. The high-speed projectile in this technique has been generated by the Horizontal Single-Stage Gas Gun (HSSGG) as shown in Fig. 1a. The HSSGG consists of high pressure reservoir, launch tube, pressure relief section and test chamber. The high pressure reservoir has an inside diameter of 7.62 cm and length of 21 cm which its volume is 9.58 x 10^{-4} m^3. The launch tube has an inside diameter of 10 mm and length of 1.1 m. The pressure relief section has a length of 15 cm, which is designed to diminish the blast wave in front of the projectile. The pressure relief section has 3 rows of holes; which each row has 4 holes having a diameter of 5 mm. The test chamber is a square tank of 40 x 50 cm in width and 60 cm in length with Polymethyl Methacrylate (PMMA) windows on two sides for visualization. The projectile is made of Polymethyl Methacrylate (PMMA), is cylindrical shape with diameter of 9.5 mm, 15 mm in length and its weight is 1.15 g as shown in Fig. 1b. This HSSGG has been employed to generate the

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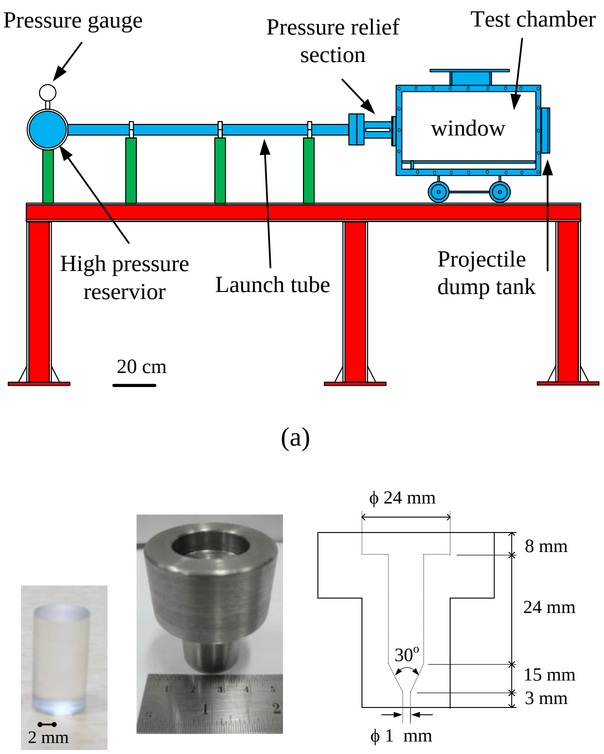
projectile velocity ranged from 50 to 250 m/s in each air pressure as the driving pressure. The nozzle connected to pressure relief section is made of mid-steel, and its dimension is shown in Fig. 1c. The projectile velocity of about 223±4 m/s was used in all experiments. Its velocity was generated by the driving pressure of 0.8 MPa.



(a)

(b) (c)

Figure 1. (a) Horizontal Single-Stage Gas Gun, (b) projectile and (c) Nozzle geometry

B. *Impact Pressure Measurement*

The supersonic liquid fuel jets generated by HSSGG are impulsive jet. Once the jet impacts on solid surface, the impact pressure reaches a high value in a very short time. This pressure is dynamics pressure or water-hammer pressure created by impact of impulsive jet. This dynamics pressure is a pressure of the high MPa up to GPa range. Hence, it is not possible to measure it by conventional instrumentation.

To measure these high pressures, the pressure sensor was designed, manufactured and calibrated. The pressure sensor is constructed with Polyvinylidence Fluoride (PVDF) piezoelectric film, a 6 mm thick of PMMA and an 8 mm thick rubber support. It is assembled in 8 mm thick housing with an outer diameter 75 mm as shown in Fig 2. This PVDF film is a flexible component which comprises a 28 μm thick of PVDF polymer piezoelectric film with screen printed Ag-ink electrodes.

The experimental setup for measuring the jet-impact pressures by a PVDF is shown in Fig. 2. Once the jet impacts on the PMMA surface, the PVDF film will respond to impact pressure giving a pressure signal that is recorded by oscilloscope as shown in Fig. 3. In the experiment, the stand-off distance from nozzle exit to the PVDF pressure sensor is varied changed by adjusting the pressure sensor holder backwards or forwards.

Figure 3 shows a load-time trace of a gasoline jet-impact at 2 cm stand-off distance from the nozzle exit. This is the pressure signal from oscilloscope in voltage signal. The voltage signal can be calculated to be pressure signal by the equation (1), being calibrated and reported by W. Sittiwong et al. [8].

$$P = (17{,}975V \times 2{,}614.4) \times (7.894757 \times 10^{-3}) \qquad (1)$$

Where P is the impact pressure of the jet (MPa) and V is voltage signal from PVDF pressure sensor (Voltage).

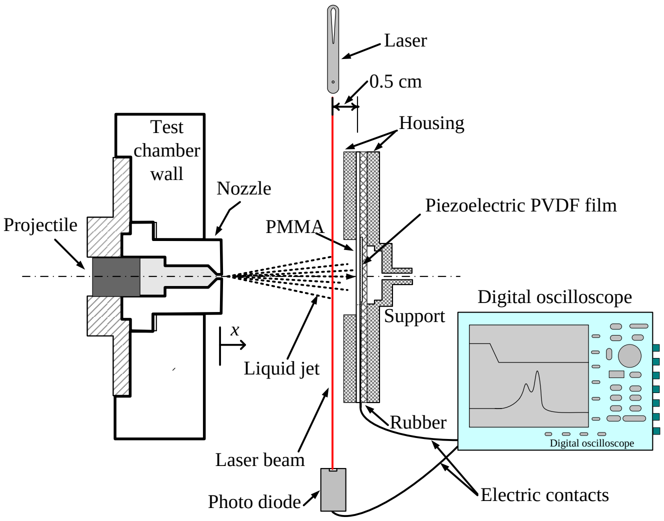


Figure 2. Experimental setup for impact pressure and jet velocity measurement

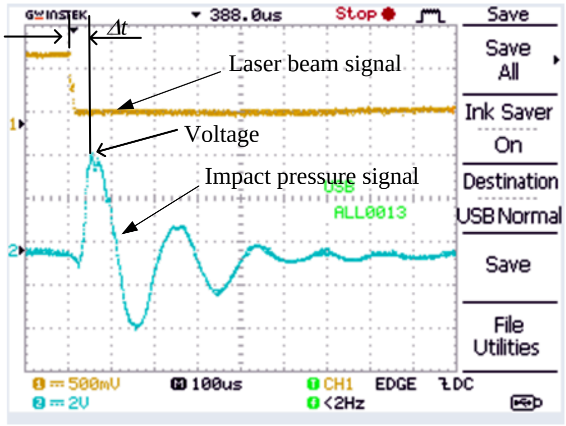


Figure 3. A load-time trace of a gasoline jet-impact at 2 cm stand-off distance

TABLE I. PROPERTIES OF LIQUID FUELS USED IN THE EXPERIMENT

Liquid type	**Formula**	**Molecular weight (g/mol)**	**Density at 20^{0}C (kg/m^3)**	**Speed of sound at 20^{0}C (m/s)**	**Kinematics viscosity at 20^{0}C (cSt)**	**Surface tension at 20^{0}C (N/m)**
Diesel	$C_{14}H_{30}$	198	840	1,350	1.8 - 4.0	0.0244
Kerosene	C_{10}-C_{14}	170	810	1,324	1.5 – 2.5	0.0235
Gasoline	C_5H_{12}	114	750	1,250	0.5	0.02
Alcohol	CH_3OH	32	785.1	1,143	1.6	0.022

C. *Jet Velocity Measurement*

In this experiment, the jet velocity was measured by laser beam interruption method. A diode laser beams cross perpendicularly to the jet path in the test chamber as shown in Fig. 2. The laser beam was placed at 5 mm in front of the PVDF pressure sensor in all experiments. When the jet tip interrupted laser beams and the jet impacted on the pressure sensor, the corresponding output signals were recorded and displayed in a digital oscilloscope. The jet travelling duration time was measured by an oscilloscope as shown in Fig. 3. From the time interval between the laser beam signal with the impact pressure signal (Δt) in Fig. 3, the jet velocities (V_j) can be calculated by:

$$V_j = \Delta s/\Delta t \qquad (2)$$

Where Δs is the distances between laser beams and the pressure sensor and Δt is the time interval of the jet over the distance Δs.

This measurement technique of impact pressure of the jets and jet velocity is specially designed and developed for this study. Both impact pressure and jet velocity being used for calculating the impact pressure in water-hammer equation can be obtained at the same time, which is the advantage of this technique. Therefore, the value of impact pressure obtained from the PVDF pressure sensor can be reasonably compared with that determined from water-hammer equation.

III. Water-Hammer Effect

When a droplet of liquid crash on a rigid surface under higher velocity or the frontal liquid in column is stopped instantaneously and sideways flow is prevented. In these cases, the pressure developed in moving column or the high pressure occur in liquid impact as a result of the water-hammer effect. The water-hammer pressure for a liquid striking a rigid surface is given by the equation [3, 6, 7].

$$P = \rho C V_j \qquad (3)$$

Where P is the impact pressure of the jet (Pa), ρ is the density of the liquid jet (kg/m^3), C is the sound speed of the liquid jet (m/s) and V_j is the jet velocity or impact velocity (m/s).

The water-hammer equation can be used for calculating the maximum pressure being developed when a jet impinges on a rigid surface. The density and the sound speed of liquid fuel jets used for calculating in the water-hammer equation can be found in Table 1.

IV. Results and Discussion

Figure 4 shows comparison between the impact pressures of supersonic diesel jet obtained from water-hammer equation and PVDF pressure sensor at various stand-off distances from nozzle exit. The impact pressures of the jet measured by the PVDF pressure sensor are higher than those the water-hammer equation at the stand-off distance of 1, 2 and 3 cm as shown in the figure. After those stand-off distances onwards, the impact pressures measured by the PVDF pressure sensor are lower than those the water-hammer equation. The values of the impact pressure obtained from the measurement and the equation are different at all stand-off distances. This may imply that the normal phenomena of supersonic liquid jets injected in air [8], being atomization, vaporization and break-up of liquid jet, importantly effect on the impact pressure of the impact-driven high-speed liquid jet injected from a single hole nozzle, while the water-hammer equation does not consider these effects. Moreover, having more slope of PVDF pressure sensor trend than that water-hammer equation verifies that the normal phenomena are significant. For kerosene, gasoline and alcohol jets, the values of the impact pressure obtained from the measurement and the equation are also different at all stand-off distances as the comparison of diesel jet.

Figure 5 shows the impact pressures of supersonic liquid fuel jets measured by PVDF pressure sensor at 1 to 6 cm stand-off distance from nozzle exit. Experiments were repeated more than three times at each individual position. The scatter of data points is reasonably small. The impact pressure of all jets decreases as the stand-off distance increases because the atomization, vaporization and breakup of jets increase as the stand-off distance increases as described by A.Matthujak et al. [8], being normal phenomena. The impact pressures of gasoline jet are the lowest at all stand-off distances because its density is the lowest. When the impact pressure of diesel, kerosene and alcohol jets at all stand-off distances were compared, the pressures are not significant because their density are not much different and the projectile velocity error is about 2% for the same projectile conditions (air pressure). Considering the slope of each jet-impact pressure trends, it was found that the trends are significant. The trend of gasoline jet is more slope than that of alcohol, kerosene and diesel jets, respectively. This is because the kinematics viscosity and surface tension of the gasoline jet are the lowest. It may imply that the lower the surface tension and the kinematics viscosity are, the higher the slope of impact pressure trend is.

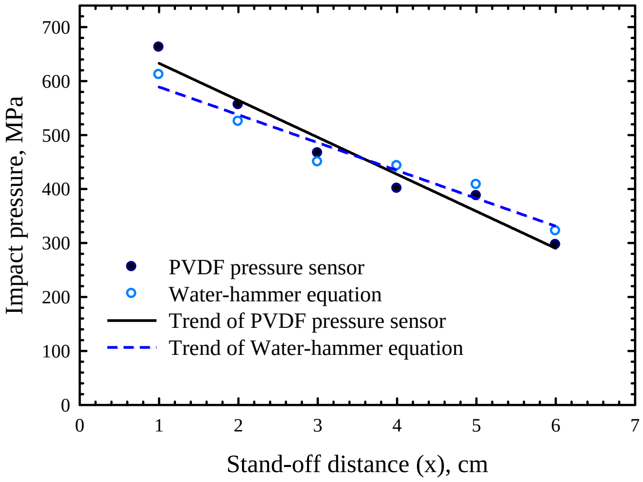


Figure 4. Comparison between the impact pressures of supersonic diesel jet obtained from water-hammer equation and PVDF pressure sensor at various stand-off distances from nozzle exit

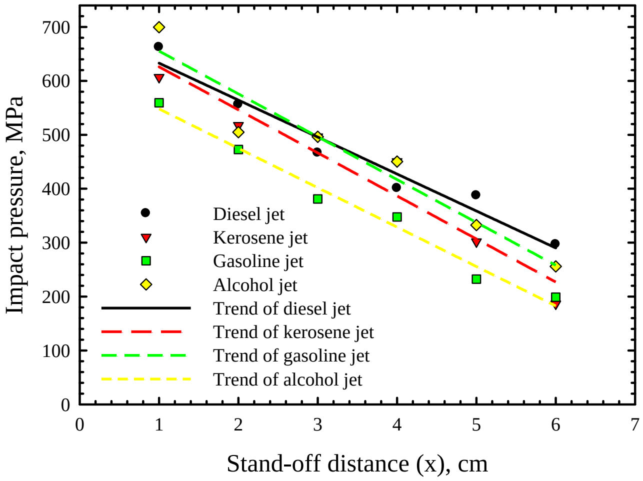


Figure 5. The impact pressures of supersonic liquid fuel jets measured by PVDF pressure sensor at various stand-off distances from nozzle exit

V. Concluding Remarks

A horizontal single-stage gas gun (HSSGG) was designed and manufactured for generating supersonic liquid fuel jets. The impact pressures of jets injected in air at 6 stand-off distances from the nozzle exit were measured by the PVDF pressure sensor. Moreover, the jet velocities could be measured for calculating the impact pressure in the water-hammer equation at the same time, which this technique is specially designed and developed for this study. From the comparison, the impact pressure calculated from water-hammer equation and measured by the pressure sensor are different since the water-hammer equation does not consider the effect of jet phenomena. Therefore, the improvement of water-hammer equation for the impact-driven supersonic liquid jet injected from the single hole of the nozzle should be done in the further study. From the measurement, the impact pressure of all jets decreases as the stand-off distance increases and the gasoline jet provided the lowest impact pressure at all stand-off distances. Moreover, it was found that the density and sound speed are significantly the physical property of jet-impact pressure. The surface tension and the kinematics viscosity are significantly the physical property for the trend of jet-impact pressure against the stand-off distance.

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