Applied Mechanics and Materials Vols. 110-116 (2012) pp 370-376
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doi:10.4028/www.scientific.net/AMM.110-116.370

Effects of Different Liquid Properties on the Characteristics of Impact-Generated High-Speed Liquid Jets

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Keywords- high-speed liquid jet, impact acceleration method, shadowgraph, shock waves

Abstract— This paper describes the study of high-speed liquid jets injected in air from an orifice. The main focus is to study the effect of different liquid properties on the characteristics of the high-speed liquid jets injected in ambient air. The high-speed liquid jets are generated by the impact of a projectile, which known as impact acceleration method, launched in a horizontal single-stage power gun (HSSPG). The conical nozzle of 30° angle with the orifice diameter of 0.7 mm was used to generate the jets. The characteristics of high-speed jets were visualized by the high-speed digital video camera with shadowgraph optical arrangement. From the shadowgraph images, the jet formation, atomization, vaporization and shock waves were obviously observed. The maximum averaged velocity of water, alcohol, n-hexane, chloroform and glycerin jets is estimated to be 1,669.03 m/s, 1,548.59 m/s, 1,420.44 m/s, 1,204.46 m/s and 1,496.97 m/s, respectively. That effect on the maximum penetration distance of the water jet is longer than that of all jets. Surface tension and latent heat are the significant physical property for jet formation, while density, kinematics viscosity and heat capacity are not.

Introduction

High-speed liquid jet has been studied for their wide applications such as cleaning and cutting technologies, mining and tunneling [1]. The high-speed liquid jet has also gained attention in combustion and medical applications [2, 3] recently. The high-speed jets in the hypersonic range, the velocity of more than 2000 m/s, have been studied and reported [4].

For commercial applications such as cutting technologies, medical and other applications in the near future, it is however unlikely to use the hypersonic jet, since the jet velocity in the applications varies just between 800-1,400 m/s. Although, there have been some studies to clarify the characteristics of high-speed liquid jet in the velocity of less than 1,600 m/s [5, 6], such studies have focused on only fuel jets, such as diesel, gasoline and kerosene, while other liquid jets have never been reported.

In this study, the characteristics of the different liquid jets in the low supersonic range, the velocity of less than 1,600 m/s, are reported. The difference characteristics of all jets, such as jet formation, penetration distance and velocity attenuation are analyzed and described by visualization.

High-Speed Liquid Jet Generation

Liquid jets are formed when pressurized liquids confined in a container are discharged through a nozzle hole and jet speeds are determined by the value of pressures. In general, the higher pressures are, the higher the jet speed becomes. However, static pressures over GPa are hard to maintain in large volume metal vessels.

To produce high-speed jets, Bowden and Brunton [7] enhanced pressures in a liquid filled a container by a momentum transfer created with a sudden impingement of a high-speed projectile as shown in Fig. 1. Then shock waves were generated inside the container creating high pressures of several GPa by shock compression which was maintained for a few hundred microseconds, which is even more effective than adiabatic compression. Hence to obtain higher jet speeds, impact speeds should be as high as possible technically.

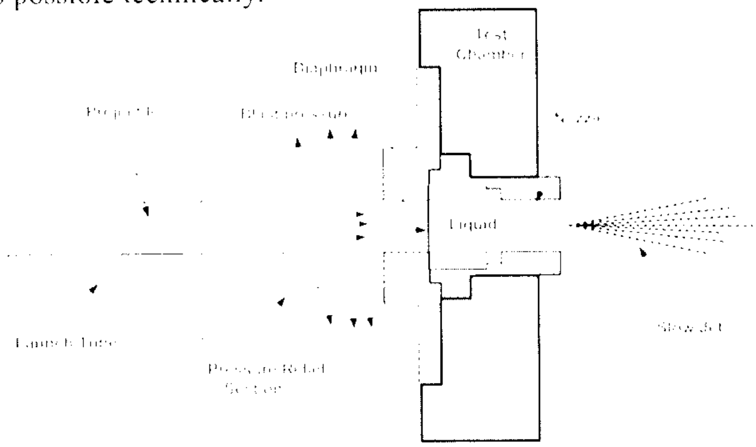


Figure 1 Experiment setup for impact acceleration method

The high velocity projectile in this technique was generated by the horizontal single stage powder gun (HSSPG) as shown in Fig. 2. The HSSPG consists of launcher, launch tube, pressure relief section and test chamber. The launch tube has a diameter of 15 mm and length of 1.5 m. The pressure relief section has a length of 38.5 cm, which is designed to diminish the blast wave in front of the projectile. The pressure relief section has 4 slots, each slot being 4 mm in width and 345 mm in length. The

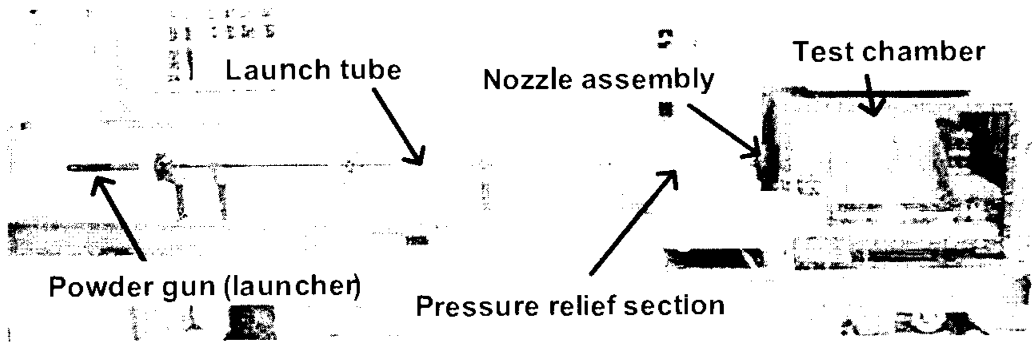
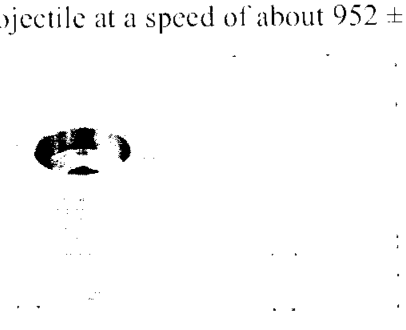


Figure 2 Horizontal Single-Stage Powder Gun (HSSPG)

test chamber is a square tank of 350 x 350 mm in width and 590 mm in length, with two polymethyl methacrylate (PMMA) windows on two sides for visualization. The projectile is made of Polymethyl Methacrylate (PMMA), is cylindrical in shape with a diameter of 15 mm and length of 8 mm (weight of 0.92 g) as shown in Fig 3a. The HSSPG can be employed to generate jet velocities of 550 to 2,290 m/s using different gunpowder weights. The nozzle that is connected to pressure relief section is made of mid-steel and its dimension is shown in Fig. 3b. In this study, gunpowder of 5 g is used which can launch the projectile at a speed of about 952 ± 32 m/s.



(a) (b)

Figure 3 Nozzle geometry

Visualization Method

In this study, a high-speed digital video camera and shadowgraph optical arrangement ware used to visualize the high-speed liquid jets as shown in Fig. 4. A Xenon lamp was used as a light source. The source light was collimated passing through a concave lens and a circular slit. The laboratory space was limited so that two plane mirrors of diameter 190 mm were combined. Two paraboloidal schlieren mirrors of diameter 300 mm were used for collimating source light beam passing the test section area. A Nikon 60 mm Macro lens was used to focus the object image on the high-speed digital video camera screen. The high-speed digital video camera is a Photron SA5 at frame rate of 30,000 f/s, maximum shutter speed of 1 μs, and 5.46 seconds record time at full resolution.

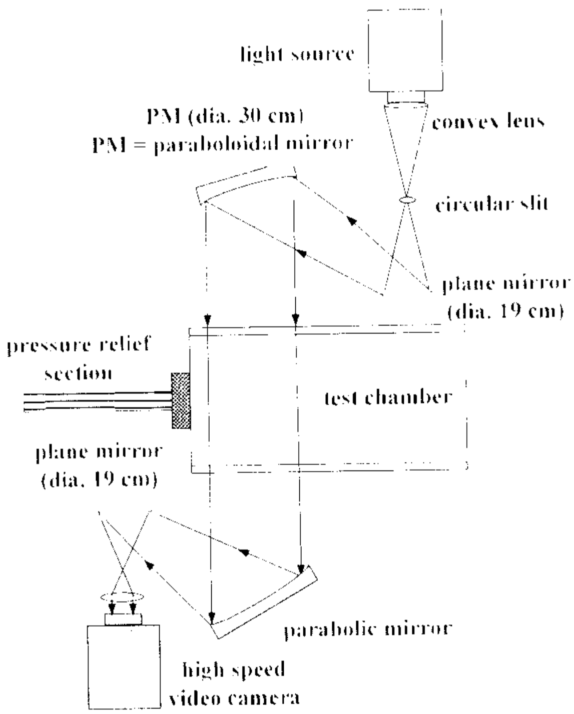


Figure 4 Shadowgraph optical setup for high-speed digital video recording

Jet Characteristics

Using a high-speed video camera, Photron SA5 could record shadowgraph images at frame rate of 30,000 f/s and shutter speed of 1 μs. Such a sequential recording is very useful to observe the jet formation. Five liquids are investigated in this study and their properties are listed in Table. 1.

In Figure 5a, only selective 8 images are presented. Jet formations of water were discharged into atmospheric air. The water jet shows the slim width and looks more elongated to be over 213 mm at 166 μs. Its averaged speed at 166 μs is 1,282 m/s and Mach number (Ms) = 3.77 in room temperature air. The jet motion is supersonic so that oblique shock waves are created over its top part and also the jet's nodes. At the earlier stage, the inclination angle of the first oblique shock wave is about 15° which corresponds to the oblique shock Mach number of 3.86.

TABLE I. PROPERTIES OF LIQUIDS USED IN THE EXPERIMENT

Liquid type	Density at 25°C (kg/m³)	Kinematics viscosity (cSt)	Surface tension at 20°C (N/m)	Heat capacity at 40°C (J/g°C)	Latent heat (kJ/kg)
Water	998	1.003 (20°C)	0.073	4.19	2,257
Alcohol	785.1	1.60 (20°C)	0.022	2.3	896
n-Hexane	654.8	0.683 (17.8°C)	0.018	2.26	365
Chloroform	1,465	0.38 (20°C)	0.027	1.05	247
Glycerin	1,259	0.648 (20.3°C)	0.063	2.43	974

The jet speed estimated from the shock inclination angle differs from that obtained from the video images. This is attributable to the fact that the relationship between the oblique shock angle and a supersonic body is valid to a supersonic solid body but in this case the jet boundary consists of distributed liquid droplets/air mixture and irregularly shaped water surface. The sound speed defined around such a jet boundary is no longer the same as that of air and slightly smaller than that in air.

In addition to this fact, the liquid jet's frontal stagnation area has a dispersed structure and a kind of ablation takes place. Not only fragmentation from bulk liquid to droplets but also vaporization on the liquid surface simultaneously takes place. As a result of it, the corresponding inclination angle of shock wave and the shock stand-off distance over the liquid jet not necessarily coincides with those over a solid body moving at the identical supersonic speed. The discrepancy also exists between the estimated jet speed from shock inclination angle and that from the video images.

Figure 5b shows alcohol jet formation. The nodes created over the alcohol jet look more bulkier than those in water jet. This trend is commonly observable in glycerin jet as shown in Fig. 5e, which is attributable to smaller values of surface tension and heat capacity. With larger surface tension the jet will not be bulged even at intermittent pressure loadings and resulting node sizes will be smaller. After elapsed time of 166 μs, the jet speed is gradually slow which can be observed the increase of shock inclination angle. Acoustic impedances of alcohol, glycerin, n-hexane and chloroform are smaller than that of water. Hence, pressure built up in these liquids by projectile impingements at identical speeds can be less than that in water. This indicates why the water jet speed is fastest. The alcohol jet is elongated more than 213 mm at 266 μs and is much slower than the water jet.

Figure 5c shows n-hexane jet formation. The general trend is not much different from alcohol jet up to 66 μs. N-hexane is very volatile and hence atomization at the jets' edge promotes vaporization. The jet boundary on the images after 133 μs looks blurred. Shock wave is attached at the jet's leading edge but after 200 μs, it becomes a detached shock wave. The jet is quickly atomized after 200 μs and its atomization process is quickest because its surface tension is smallest.

Figure 5d shows chloroform jet formation. Three steps of impulsive accelerations [6] are clearly observed at 100 μs, which can be observed the change in shock angle. The general trend of the chloroform jet formation is similar to the alcohol jet formation until 200 μs because their surface tensions are quite equal, these being 0.022 N/m and 0.027 N/m, respectively. After 200 μs, the chloroform jet is quite similar to the n-hexane jet. The jet is attenuated as its leading edge is not elongated quickly as seen in the last three frames from 200 μs to 333 μs. Detached shock waves are clearly visible on the second and the third frames.

Figure 5d shows glycerin jet formation. The general trend is similar to alcohol jet even though their surface tensions are quite different, these being 0.063 N/m and 0.022 N/m, respectively. The similarity between glycerin and alcohol jets may be because their latent heats are quite equal, these being 974 kJ/kg and 896 kJ/kg, respectively.

As seen in Fig. 5, jet tips and frontal parts of nodes have dispersed structures and their boundaries are blurred. Hence, distinct shock fronts were hardly formed by these obscured fronts but compression waves were driven, which gradually coalesced into distinct oblique shock fronts. As a result of this, at the earlier stage of their formations, their edges look not necessarily a clear boundary but appear to be a bumpy boundary. Moreover, it was found that surface tension and latent heat are the significant physical property for jet formation, while density, kinematics viscosity and heat capacity are not.

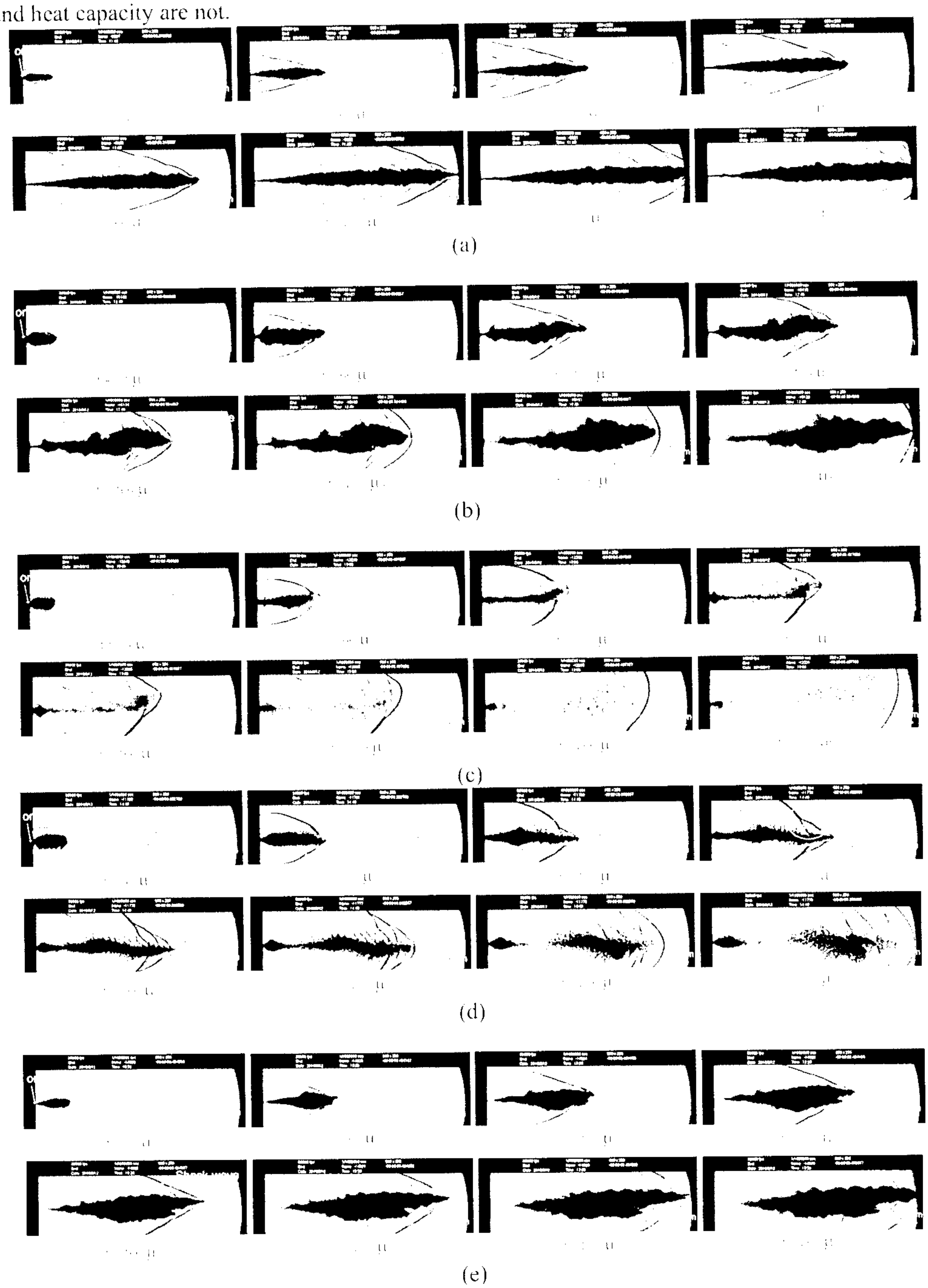


Figure 5 Jet formation (a) Water jet (b) Alcohol jet (c) n-Hexane jet (d) Chloroform jet (e) Glycerin jet

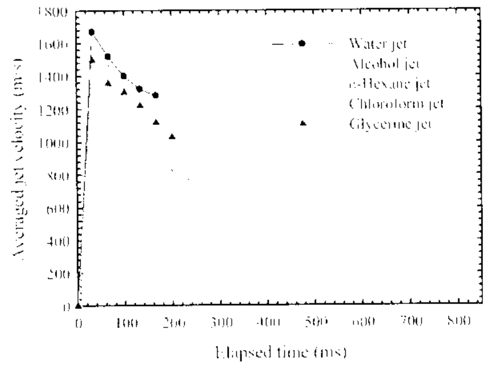


Figure 6 Effect of difference liquid jets on averaged jet velocity

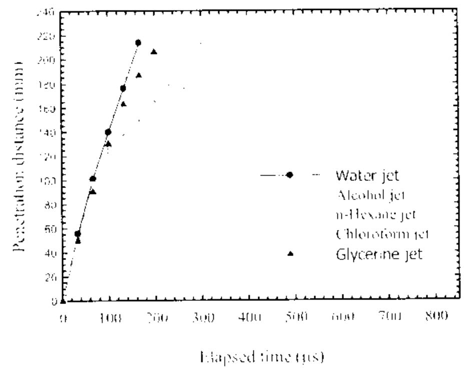


Figure 7 Effect of difference liquid jets on jet penetration distance

Fig. 6 shows the effect of different liquid jets on the averaged jet velocity. During the maximum velocity point and the emerging time of 33 μs, the velocity of all liquid jets gradually drops as obviously seen in the figure. The maximum averaged velocity of water jet is fastest, it being estimated to be 1,669.03 m/s. The next one is alcohol, glycerin, chloroform, and n-hexane jets, respectively, these being estimated to be 1,548.59 m/s, 1,420.44 m/s, 1,204.46 m/s and 1,496.97 m/s, respectively. That effect on the penetration distance of water jet is longest at the same elapsed time as shown in Fig. 7. The second one is alcohol, glycerin and chloroform jets, respectively. The shortest penetration distance is n-hexane jet. It can be concluded that the higher surface tension is, the faster the maximum averaged jet is and the longer the jet penetration distance is even though the alcohol jet does not play this role. It may be due to the latent heat of the alcohol jet which effects on the atomization and vaporization process. However, the different characteristics of alcohol jet from all liquid jets still needs more experiments to clearly describe or confirm the occurrence.

Concluding Remarks

This study describes the characteristics of high-speed water, alcohol, n-hexane, chloroform and glycerin jets injected in ambient air. Using a high-speed digital video camera with shadowgraph optical arrangement, the dynamic behaviors of all jets and their shock waves were clearly observed. Formation of water, alcohol and glycerin jets are similar, while formation of n-hexane and chloroform jet are similar which atomization was obviously observed in the later stage. Special behaviors being three steps of impulsive accelerations and change in shock angle were clearly observed in chloroform jet. The maximum averaged velocity of water, alcohol, n-hexane, chloroform and glycerin jets is estimated to be 1,669.03 m/s, 1,548.59 m/s, 1,420.44 m/s, 1,204.46 m/s and 1,496.97 m/s, respectively. That effect on the maximum penetration distance of the water jet is longer than that of all jets. Surface tension and latent heat are the significant physical property for jet formation, while density, kinematics viscosity and heat capacity are not.

Acknowledgment

The authors are grateful to Thailand Research Fund (TRF, contact No.MRG5180046), Department of Mechanical Engineering, Faculty of Engineering, Ubon Ratchathani University (UBU), National Research Council of Thailand (NRCT) and Thailand Toray Science Foundation (TTSF) for financial support.

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Applied Mechanics and Materials

Country: Switzerland

Subject Area: Engineering

Subject Category: Engineering (miscellaneous)

Publisher: Scitec Publications Ltd.. **Publication type:** Book Series. **ISSN:** 16609336

Coverage: 2005-2010

H Index: 6

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