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EVALUATION OF THE CUMULATIVE FORMATION OF HIGH-SPEED LIQUID JETS*

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ABSTRACT: This paper describes the generation of pulsed, high-speed liquid jets using the cumulation method. This work mainly includes (1) the design of the nozzle assembly, (2) the measurement of the jet velocity and (3) flow visualization of the injection sequences. The cumulation method can be briefly described as the liquid being accelerated first by the impact of a moving projectile and then further after it enters a converging section. The experimental results show that the cumulation method is useful in obtaining a liquid jet with high velocity. The flow visulization shows the roles of the Rayleigh-Taylor and Kelvin-Helmholtz instabilities in the breakup of the liquid depend on the jet diameter and the downstream distance. When the liquid jet front is far downstream from the nozzle exit, the jet is decelerated by air drag. Meanwhile, large coherent vortex structures are formed surrounding the jet. The liquid will break up totally by the action of these vortices. Experimental results showing the effect of the liquid volume on the jet velocity are also included in this paper. Finally, a method for measuring the jet velocity by cutting two carbon rods is examined.

KEY WORDS: high-speed liquid jet, cumulation method, velocity measurement, visualization

1. INTRODUCTION

High-speed liquid jets are often seen in rain erosion simulation of aircraft and missiles, Jilbert and Field[1] and jet cutting of materials, Kobayashi[2]. In the generation of jets, it is technically interesting to know how to operate the experimental facility at the optimum condition to obtain the jet velocity most efficiently. This is described by Shi and Takayama[3], Shi and Itoh[4], Shi and Itoh[5]. In the earliest study of a pulsed high-speed liquid jet, Bowden and Brunton[6] put the liquid in a nozzle and then used a slug impacting on the nozzle with the free surface of the liquid facing the atmosphere. This is the so-called direct impact method. Alternatively, in the experiment of Edney[7], a converging section was placed in front of the liquid cylinder so that the liquid was accelerated twice: firstly by the shock wave due to the impact of the prijectile; secondly by the converging boundary of the nozzle. The latter is called the cumulation method and it can produce a hypervelocity liquid jet, Shi et al.[8,9]. The purpose of this paper is to quantitatively determine the increase of the jet velocity by these two methods. In the gas gun experiment of Shi et al.[10], for a 1mm diameter nozzle and the direct impact method, it was found that the maximum velocity of the liquid jet was about 670m/s. Here, it is shown that, at identical conditons, the cumulation method can generate a liquid jet to 900m/s.

2. EXPERIMENTAL ARRANGEMENT

Fig. 1 shows the experimental facility for the

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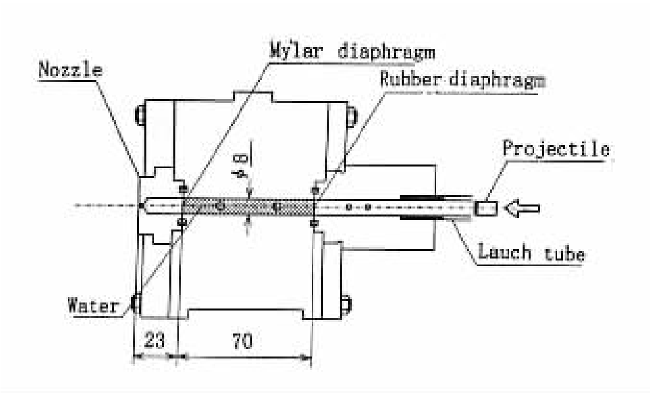
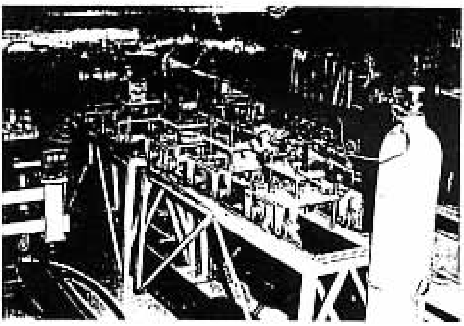
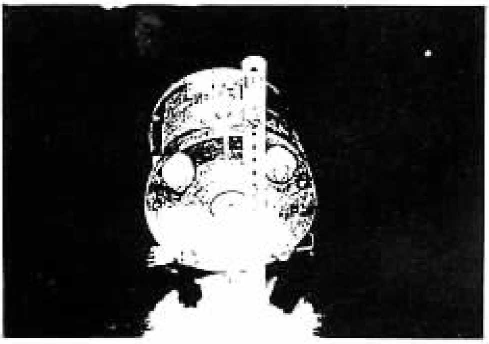


Fig. 1 Experimental device for the cumulation method for generating a high-speed liquid jet



2(a) Gas gun



2(b) Nozzle

Fig. 2 Photographs of the experimental facilities

cumulation method for generating high-speed liquid jets. The liquid (water) cylinder of 8mm diameter and 70mm length is sealed in a specially designed container by a 9μm Mylar diaphragm in the front (downstream) and a 2mm rubber diaphragm at the rear (upstream). A brass/nylon projectile accelerated from a gas gun (see Fig. 2(a) or Shi et al.[10]) pushes the liquid cylinder making it flow into the brass nozzle. The nozzle has a total length of 23mm and is 8mm diameter at its upstream section. It has 120° of taper angle to the nozzle exit. Three nozzles with exit diameter of 1mm, 2mm and 3mm were tested. The effect of the liquid cylinder length on the jet formation was also tested. The projectile has a total length of 12mm, a 2mm thick brass plate with 6.2mm dimeter being embedded in a nylon body with 7.2mm diameter. The nozle device is shown in Fig. 2(b). Fig. 3 shows the schematic of the flow visualization system. The xenon flash (NP-1A, 180ns exposure time, Sugahara Laboratory) is placed vertically with the open shutter camera in horizontal. When the thin wire in the launch tube is cut by the projectile and the synchronization is determined by the delay unit, the jet image is taken.

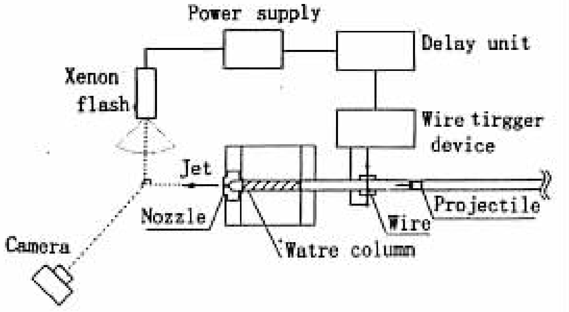


Fig. 3 Schematic of the flow visualization system

3. RESULTS

3.1 *Miximum jet velocity*

The velocities of the jets from a 1mm diameter nozzle at different rupture pressures are shown in Fig. 4. Jet velocities were obtained by measuring the difference of the time when the jet leading edge cuts two laser beams placed 40mm apart. When the rupture pressures rnage from 1.10MPa to 1.20MPa, the maxumum jet velocity of 950m/s is obtained. The calibrated relationship between the rupture pressure and projectile velocity is given in Fig. 5, from which the projectile velocity is known to be about 270m/s when the rupture pressure is around 1.15MPa. For the jets from the 2mm diameter nozzle, Fig. 6 shows that the maximum velocity is 960m/s which is close to the value of the 1mm diameter nozzle. Fig. 7 shows that the jet velocities from the 3mm diameter nozzle are much slower than the jets from the 1mm and 2mm diameter nozzles. Considering that the injection of the jet is a decelerating process, the experiment has shown that the design of the apparatus for the cumulation method of Fig. 1 is best for the generation of 2mm diameter liquid jets.

3.2 *Unsteadiness of the jet*

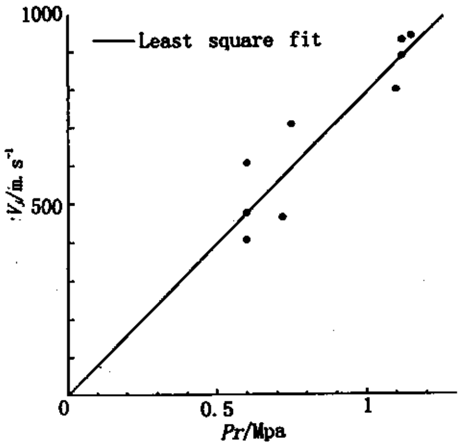


Fig. 4 Jet velocity vs the various diaphragm rupture pressures

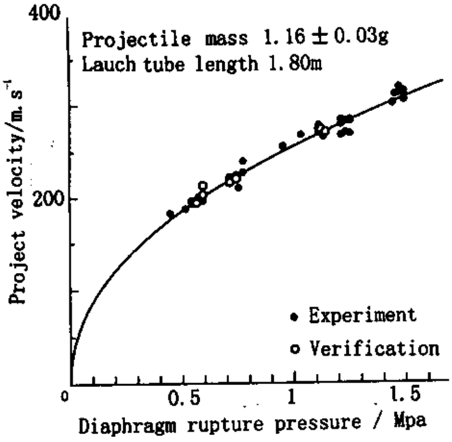


Fig. 5 The terminal velocity of the projectile at various diaphragm rupture pressure

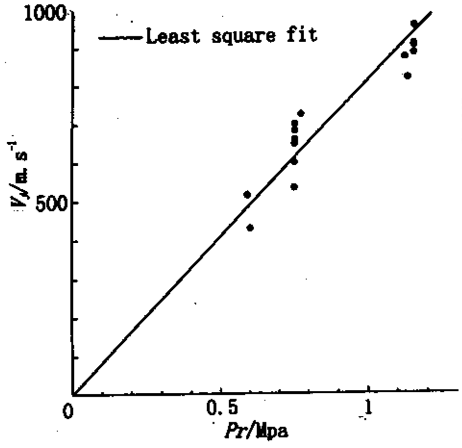


Fig. 6 Jet velocity vs the various diaphragm rupture pressures

Fig. 8 shows a group of photographs of the high-speed liquid jets from the 2mm nozzle when the rupture pressures are 1.15-1.20MPa. It is seen that at almost identical experimental conditions, the shape of every jet from Fig. 8(a) to Fig. 8(f) is different. This means that such liquid jets are not easy to be simulated numerically by any method, for example the KIVA code (Utsumomiya et al.[11]). The reasons for this are related to the jet structure and the high velocity of the jet. For the jet from the 1mm nozzle, it is found that the liquid is atomized just after leaving the nozzle exit and the roles of the Rayleigh-Taylor and Kelvin-Helmholtz instabilities are not obvious. Since the jet has a high initial velocity (with Mach number of about 3) and a small diameter, the breakup occurs in the entire jet. In other words, the liquid jet is completely disintegrated. The jet behaves very similar to a typical diesel spray, Beal and Reitz[12], Andrews[13]. It is believed that the aerodynamic effect dominates the breakup process at the beginning, Fuller et al.[14]. The fluid instabilities play a later role.

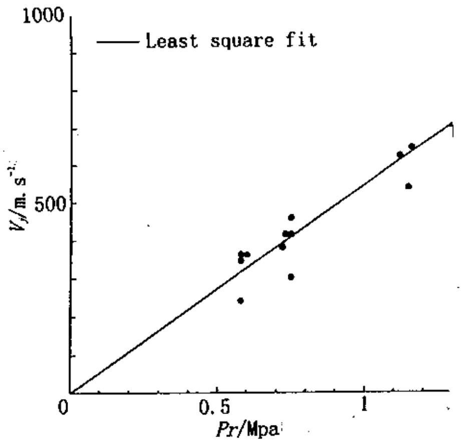


Fig. 7 Jet velocity vs the various diaphragm rupture pressure

The jet from the 3mm nozzle is composed of a central liquid core and a surrounding shroud of spray. Before the formation of the jet, the fluid flow in the 3mm nozzle is incompressible so that when the liquid just emerges from the nozzle exit, the jet diameter is equal to the nozzle diameter. However, due to the aerodynamic drag acting on the jet front, the fluid particles must turn towards the radial direction in order to form a liquid sheet. The sheet would quickly be folded back due to the air drag but meanwhile it is atomized by the Kelvin-Helmholtz instability. The X-ray radiongraphy of Warken and Krehl[15] also confirms that the liquid core/spray shroud structure exists from 4mm diameter liquid jets. The jets from the 2mm nozzle shown in Fig. 8 behave a manner between the 1mm

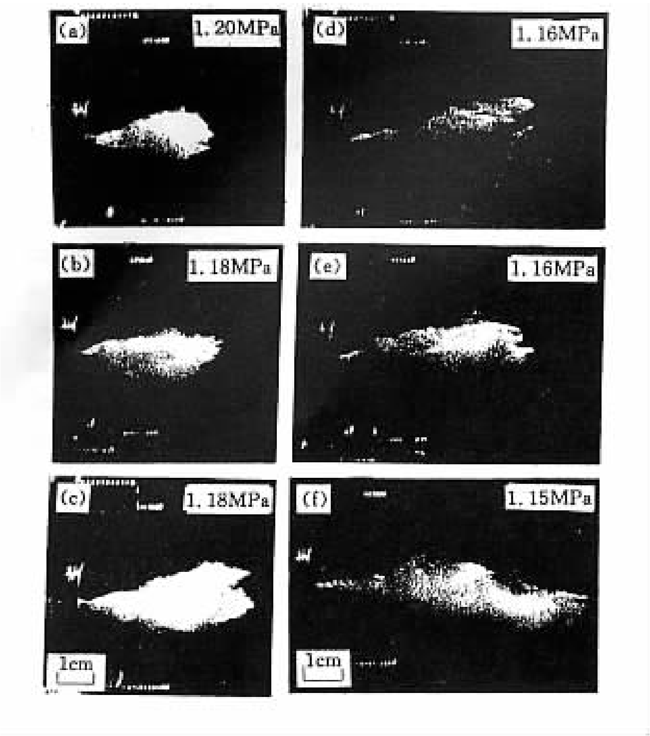
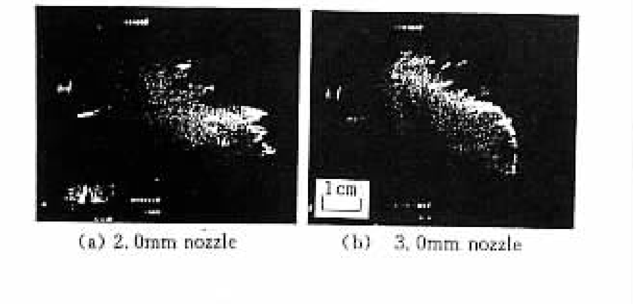


Fig. 8 Unsteadiness of the high-speed liquid jet. 2.0mm nozzle. The rupture pressure from (a) to (f) are arranged from 1.15MPa to 1.20MPa

jet and the 3mm jet. Aerodynamic breakup and non-aerodynamic breakup are both involved. The jets certainly consist of continuous fluid (the core) and discrete droplets (the spray). The jets have a large spray diameter but they do not like a typical diesel spray.

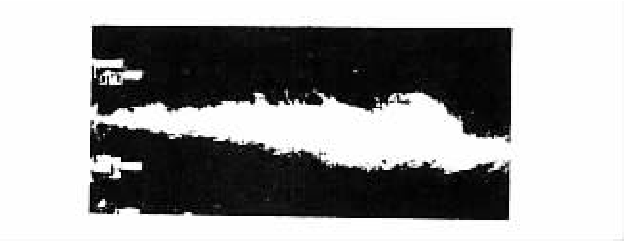


(a) 2.0mm nozzle (b) 3.0mm nozzle

Fig. 9 Explosive breakup of the liquid jet. Rupture pressures: 1.15MPa

3.3 *Explosive breakup of the jet*

Sometimes, the jets reach an explosive breakup phase as shown in Figs. 9(a) and 9(b). This type of breakup is much more severe that the explosive breakup of a liquid jet caused by a swirling coaxial gas jet (Hopfinger and Lasheras[16]). In the experiment using the direct impact method by Shi and Takayama[3], explosive breakup was also found and they described it as a rapidly expanding bubble. It is believed that the collapse of an air bubble in the liquid causes the breakup.



10(a) Rupture pressure 1.45MPa. Impact velocity of the projectile 307m/s

10(b) Rupture pressure 1.34MPa. Impact velocity of the projectile 295m/s

Fig. 10 Formation of large vortex structure around the liquid jet from the 3.0mm nozzle

3.4 *Formation of large vortex structure*

When the xenon flash of 180ns exposure time was replaced by a strobe light of 25μs exposure time, a large vortex structure (Vanlerberghe et al.[17]) was found to exist around the liquid jets of the 3mm nozzle, (see Figs. 10(a) and 10(b)). For the jets from the 1mm nozzle, no such a structure could be found. Instead, a helical vortex structure was visible in the cneter part of the spray. This is because the 1mm jets are atomized and decelerated too quickly. In this case, the convective Mach number (Messersmith and Dutton)[18] of the jet is too low to allow the shear layer to develop. For the jets from the 3mm nozzle, as discussed above, when the surrounding spray is decelerated, the central liquid core still maintains a high-speed. The velocity difference between the liquid core and the spray causes the large vortex structure seen in Fig. 10.

3.5 *Effect of the liquid cylinder length*

The nozzle device in Fig. 1 is one in which the length of the liquid cylinder can be changed. Fig. 11 shows the measured relationship of the jet velocity vs liquid cylinder length. In this case the distance from the first laser beam to the nozzle exit is 25mm. The distance between the two laser beam is 40mm. It is known that the jet velocity does not change very much when the liquid cylinder length is increased from 30mm to 70mm. The jets of the 2mm nozzle were tested and the measured velocities represented the averaged value at the standoff distance of 45mm. Comparing with Fig. 6, it is seen that the large reduction in downstream velocity also occurs for the 2mm jets.

In an effort to measure the jet velocity by cutting two 0.5mm diameter carbon rods, it was found that the measurement gave a lower value of the velocity than obtained from the laser cutting method. That was because the impact of the jet on the first carbon rod caused breakup of the jet which then decelerated it before it arrived at the second rod. For measuring the jet velocity of small diameter, this method is not recommended.

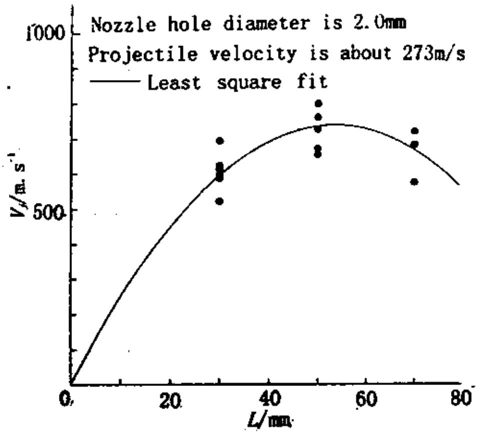


Fig. 11 Jet velocity vs water column length

4. CONCLUSIONS

(1) Using the cumulation method, a higher velocity can be obtained for pulsed liquid jets than by using the direct impact method. The design shown on Fig. 1 is a successful one.

(2) The liquid jets behave in a quite unstable manner perhaps due to the acceleration of the liquid in the nozzle converging section and the subsequent high jet velocity. Aerodynamic breakup and non-aerodynamic breakup are involved in the atomization of the liquid depending on the diameter of the jet. A large vortex structure exists around the jets from the 2mm and 3mm nozzles. The jets from the 1mm nozzle look like a typical diesel spray.

(3) Within the experimental scope of the research, the variation of the length of the liquid cylinder does not apparently affect the jet velocity. This may show that part of the liquid goes back under high pressure in the nozzle and part of the liquid flows through the nozzle to appear as a jet.

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