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Research paper

Fundamental Study of Electromagnetic Actuated Needle-Free Jet Injection

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Abstract

The objective of this paper is to preliminarily study the needle-free jet injection by electromagnetic actuator. The jets were generated by electromagnetic actuator, being designed and manufactured for this study. Effects of orifice diameter of the nozzle, travelling distance, voltage and liquid volume on jet velocity and impact pressure were investigated by laser beam interruption method and PVDF pressure sensor respectively. Moreover, the evolution of jet penetration during the injection into 20% Polyacrylamide gel was visualized by high-speed video camera. It was found that the electromagnetic actuator with the orifice diameter of 0.2 mm at travelling distance of 5 mm and voltage of 500 Volt at all liquid volumes can be applied for needle-free jet injection. The introductory channel as well as circular dispersion was obviously observed seen from the evolution of jet penetration into 20% Polyacrylamide gel.

Keywords: *Electromagnetic actuator; Needle-free jet injection; velocity; impact pressure; Polyacrylamide gel*

1. Introduction

It is known well that the high speed liquid jet can apply for many engineering applications such as jet cutting [1], fuel injection [2] and others. In addition, it also can apply for medical application such as micro jet cutting [3], drilling bone [4] and drug delivery without needle or needle-free jet injection, being popularly medical application.

In order to deliver the drug using needle-free jet injection, the jet speed is 100 - 200 m/s [5] and its impact pressure is more than 15 Mpa [6]. Nowadays, energy sources of commercial needle-free jet injector have two categories, being spring and compressed gas. The advantages of spring are compact and low cost. However, its disadvantages are the fatigue of spring when it is used for long time and the nonadjustable jet velocity. The advantage of compressed gas is the precision of jet velocity in each drug deliveries for long time. The popularity of gases are Carbon-dioxide and Helium gas [6] However, its disadvantages are large system, expensive and the noise of gas release, which makes patient scared. Recently, there have been invented the new energy source for drug delivery, being electric power.

In 2007, Stachowiak et al. [7] applied Piezoelectric as the actuator for needle-free jet injection. The actuator was able to deliver the drug at 10 µL, being very low volume. In 2012, Taberner et al. [5] invented an electromagnetic actuator for deliver drug. The actuator has enough potential for drug delivery. However, the performance of actuator for drug delivery has not been reported.

Therefore, this research is to study the performance of electromagnetic actuator for needle-free jet injection. Effects of voltage (V_c), travelling distance (x_t), orifice diameter of nozzle (d), liquid volume (V_L) on jet velocity (V_j) and impact pressure are investigated. Moreover, the evolution of jet penetration into 20% Polyacrylamide gel is presented.

2. Materials and Methods

2.1 Needle-Free Jet Injector

The device of needle-free jet injection was created based on impact driven method [8] as shown in Figure 1. It consists of actuator, nozzle and power source. The actuator is made from high density magnetic (Neodymium magnet, NdFeB) inserted inside the bobbin. The bobbin is entwined by 1,600 rounds of 0.32 mm in diameter of copper wire as copper coil. Nozzle is made from mid-steel and it has L/d of 4 and 40˚ of cone angle [9]. The capacitor unit of 600 Volt and 5,400 µF is used as power source, being charged by power supply.

To generate the liquid jet, the capacitor unit was charged by power supply until it has the required voltage. The electric power from the capacitor unit was discharged to the copper coil for generating electromagnetic field and then the bobbin was moved. When the bobbin impacted the piston inserted inside nozzle, the piston was driven liquid contained inside the nozzle out from the nozzle orifice as the jet. The liquid used as drug in this study is water.

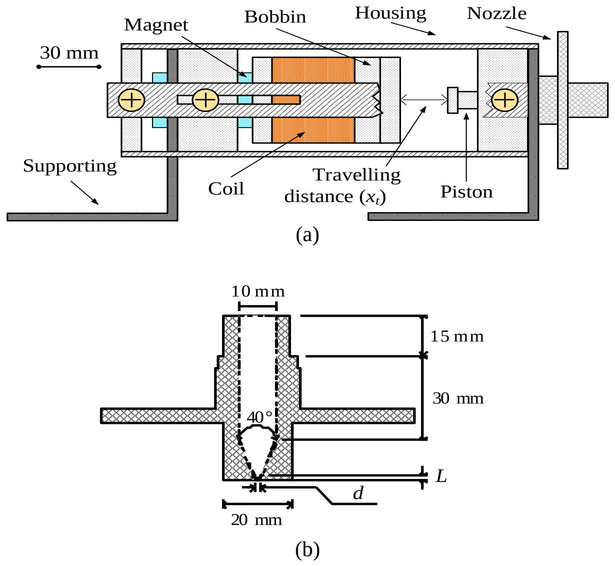

Figure 1: (a) Electromagnetic actuator for needle-free jet injection and (b) Nozzle

2.2 Velocity Measurement

Jet velocities were measured by laser beam interruption method as show in Figure 2. Two diode laser beams cross perpendicularly to the test area and are detected by individual photodiodes. The first laser and photodiode are placed at 2 mm from the nozzle exit. The distance between two lasers is 16 mm. When the water jet interrupted laser beams, the corresponding output signals are recorded and displayed in a digital oscilloscope. From the signal, the jet velocities can be calculated by the below equation.

$$V_j = \frac{S}{\Delta t} \tag{1}$$

Where V_j is the jet velocity (m/s), S is distance between two lasers (16 mm) and Δt is the time of flight over 16 mm (s).

2.3 Impact Pressure Measurement

To measure the impact pressure, the pressure sensor was designed, manufactured and calibrated [10]. The pressure sensor was constructed with Polyvinylidence Fluoride (PVDF) piezoelectric film. It is assembled on 25 mm thick of PMMA support. The PMMA housing dimension is 45x45 mm2 as shown in Fig 2. This PVDF film is a flexible component which comprises a 28 µm thick, width 15 mm and length 25 mm of PVDF polymer piezoelectric film with screen printed Ag-ink electrodes.

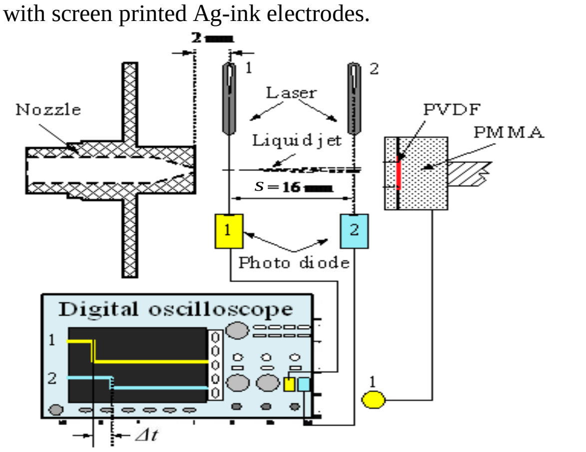

Figure 2: Experimental setup for impact pressure and jet velocity

The experimental setup for measuring the jet-impact pressures by a PVDF is shown in Figure 2. Once the jet impacts on the PVDF pressure sensor, the PVDF pressure sensor will respond to impact pressure giving a pressure signal that is recorded by oscilloscope as shown in Figure 3. In this experiment, the stand-off distance from nozzle exit to the PVDF pressure sensor is 3 mm.

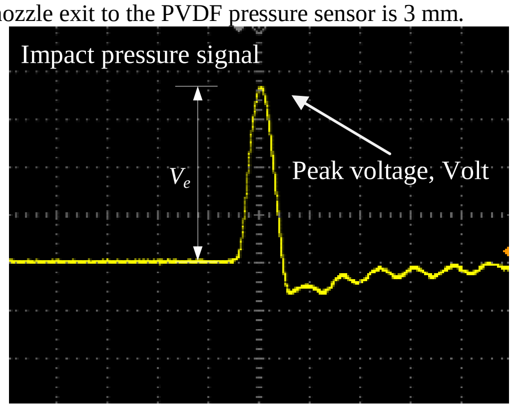

Figure 3: A load-time trace of a water jet-impact at V_L = 0.3 mL, x_t = 5 mm and V_c = 500 Volt.

Figure 3 shows a load-time trace of a water jet-impact. This is the pressure signal from oscilloscope in voltage signal. The voltage signal can be calculated to be pressure signal by the equation (2), being calibrated for this experiment.

$$P = 35.268V_e + 7.8274 \tag{2}$$

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

2.3 Polyacrylamide Gel

To predict the behavior of the dispersion of water jet for this study, water jet being used as drug was injected into Polyacrylamide gel. 20% - 30% Polyacrylamide gel was generally used for drug delivery study because it has clearness [5] and its young modulus is similar to human tissue, being 0.22 - 0.38 MPa [11]. In this study, 20% Polyacrylamide gel were prepared by mixing an appropriate volume of 40% acrylamide stock (i.e. 37.5 acrylamide/1 bis-acrylamide; BioRad Laboratories) with distilled water. The Polymerization was initiated by the addition of ammonium persulfate (APS) and N,N,N',N'-tetramethylethylenediamine (TEMED).

3. Results and Discussion

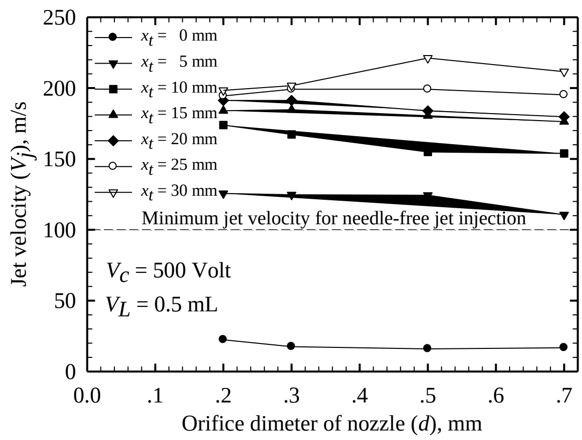

Figure 4: Effect of orifice diameter of nozzle on jet velocity at various travelling distances at V_L = 0.5 mL and V_c = 500 Volt.

Figure 4 shows effect of orifice diameter of nozzle on jet velocity at travelling distance of 0 - 30 mm. Experiments were repeated more than five times at each individual position. The scatter of data points is reasonably small. The jet velocity of water jet increased as the travelling distance increased at all orifice diameters of nozzle because of increasing the momentum transfer of copper coil. However, the orifice diameter has an indescribably significant effect on various jet velocities. The maximum jet velocity of 221.20 m/s was provided at d = 0.5 mm and x_t = 30 mm. However, d = 0.2 mm at x_t = 5 mm were selected to apply for needle-free jet injection because d = 0.2 mm has the same diameter of drug delivery by needle and x_t = 5 mm was able to generate the jet velocity at higher than 100 m/s, being the minimum velocity for needle-free jet injection.

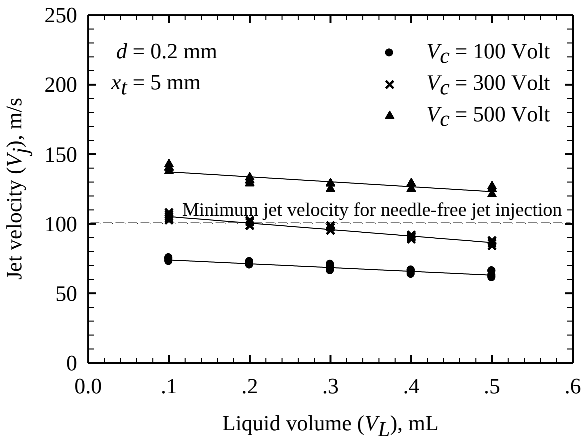

Figure 5: Effect of liquid volume on jet velocity at 100 Volt, 300 Volt and 500 Volt

Figure 5 shows effect of liquid volume inside the nozzle on jet velocity at 100 Volt, 300 Volt and 500 Volt. The jet velocity decreased when the liquid volume increased at all voltages because of increasing the back pressure in the nozzle based on theory of compressible fluid dynamics. At all liquid volumes, the jet velocity increased as the voltage increased, being the normal behavior. However, the 500 Volt can generate jet velocity of higher than 100 m/s, being the minimum jet velocity for needle-free jet injection, at all liquid volumes.

Figure 6 shows effect of liquid volume on impact pressure at 500 Volt. The impact pressure was measured at 3 mm from nozzle exit. The impact pressure decreased when liquid volume increased because jet velocity decreased as show in Figure 4. The maximum and minimum impact pressures were 20.91 and 16.34 MPa at 0.1 mL and 0.5 mL, respectively, which were higher than the minimum impact pressure of 15 MPa for needle-free jet injection [6]. Therefore, it is concluded that this actuator is able to penetrate drug into the human skin.

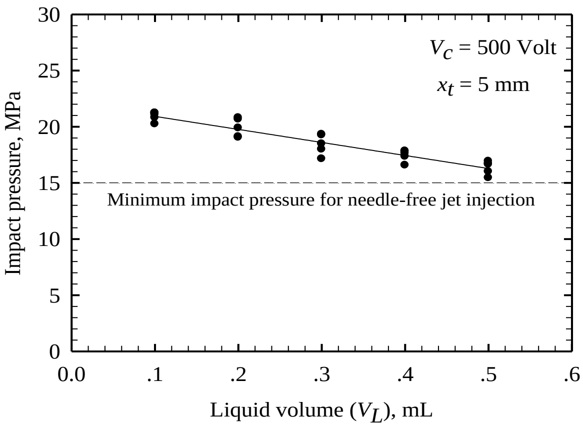

Figure 6: Effect of liquid volume on impact pressure at 500 Volt.

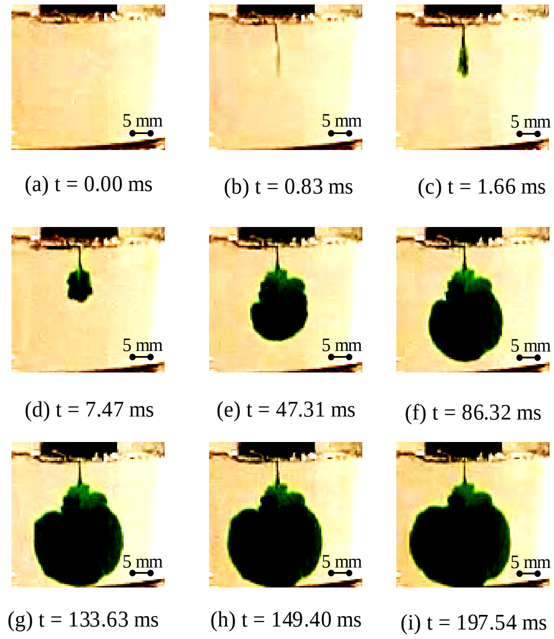

Figure 7: Evolution of jet penetration during the injection into 20% Polyacrylamide gel at 500 Volt, 0.5 mL.

Figure 7 shows the evolution of jet penetration during the injection into 20% Polyacrylamide gel at 500 Volt, 0.5 mL. The evolution of jet penetration was recorded by high-speed video camera, Casio Exilim Pro EX-F1 with frame rate of 1,200 fps. From the images, the introductory channel as well as circular dispersion was obviously observed. The evolution of jet penetration can be divided into three periods. The first period is the start of injection, as shown in Figure 7(a). The second period is called penetration period, as shown in Figure 7(b). In this period, the jet has the maximum velocity and maximum impact pressure to penetrate the gel. The depth of penetration depends on the velocity and impact pressure. This period takes shorter time than next period. The last period is called the dispersion of liquid jet in the gel, as show in the Figure 7(c-i). The time of this period depends on the liquid volume.

4. Concluding Remarks

From the experimental results, it is concluded that:
1. The jet velocity of water jet increased when the travelling and the voltages increased whereas the liquid volume decreased.
2. The orifice diameters between 0.2 – 0.7 mm have an indescribably significant effect on various jet velocities
3. The impact pressure decreased when the liquid volume increased.
4. The electromagnetic actuator at d = 0.2 mm, x_t = 5 mm, V_c = 500 Volt and all liquid volumes can be applied for needle-free jet injection.
5. The introductory channel as well as circular dispersion was obviously observed from the evolution of jet penetration into 20% Polyacrylamide gel.

Acknowledgement

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