High Speed Liquid Jet Generation for Needle-Free Injector by Impact Driven Method

Prachya Mukda
Department of Mechanical Engineering, Phetchaburi Rajabhat University,
38 Moo 8, Tambon Nawung, Amphoe Mueang, Phetchaburi, Thailand
Corresponding Author: mukdaen@gmail.com

Abstract

Currently, most of commercial needle-free jet injectors generate the liquid jet by a method called "driving object method" (DOM). However, the reliability and efficiency are still questioned. This paper proposes a new concept of jet generation method, known as "impact driven method" or IDM. A prototype of an IDM jet injector is tested to compare with a commercial device (Cool.click). Jet injection processes are visualized both in air and in 20% polyacrylamide by high speed photography. In this study, the first pulse gives a shorter erosion stage and then immediately the second pulse follows and provides a better penetration, wider lateral dispersion, and considerably less back splash. Hence, lower pain level and higher delivery efficiency should be achieved. It can be concluded that the IDM concept is highly feasible for implementation in real applications, either for human or animal injection. However, the control and accuracy of IDM still needs to be carefully investigated.

Keywords: Needle Free Jet Injector, Impact Driven Method, High Speed Liquid Jets.

Introduction

High speed liquid jets have been successfully applied to many appropriate technologies or applications, such as cutting, automobile, combustion, and medical engineering. Recently, in medical engineering, researchers have been attempting to use high speed liquid jets in a device called a "jet injector." This medical device employs a high speed liquid jet to replace the needle in a hypodermic syringe and is sometimes called "needle free jet injection." A high-speed intact jet penetrates into the epidermis and disperses into the targeted tissue. Currently, jet injectors are generally powered by gas, compressed spring, and electromagnet.

The main advantages of jet injectors are that they are easy to handle and readily accepted by children or people with needle phobia. Additionally, a large number of medications can be made in a short time and available with various traditional drug models [1]. Moreover, results from several studies have indicated that jet injection can lead to a higher drug activation rate when compared to a hypodermic syringe because liquid drug delivered via jet injection can be dispersed more widely in the tissue due to the high pressure driving the liquid medication [2, 3]. This wider dispersion has also been observed and confirmed in the study of Baxter et al. [4].

Currently, a large number of jet injector devices are commercially available in the market, some of them being in the development stage. Although these jet injectors are used in commercial applications, they are not acceptable for patients because the reliability and control of jet injection are too low [5]. When reliable control and accuracy is not accomplished, it becomes a weakness for the jet injector device. It is found that the jet injector devices were sometimes associated with higher levels of pain and more local reactions compared to proper hypodermic syringes [6]. Moreover, in certain devices, there may be blood contamination in the head of the injector after injection because the device generates too high of a jet velocity, resulting in blood splashed back from the patients [7]. This problem does not occur every time but rather under non-optimized operating conditions, such as loading too little volume of the liquid drug in a fixed power jet injector [8].

Regarding the jet generation method, all of the jet injector devices in current generate liquid jet by the principle called the "driving object method" (DOM) which shows in Figure 1 (a). The liquid contained in the nozzle cavity is driven by an object, such as a piston, which increases the liquid pressure by direct contact, thereby accelerating the jet to a high efflux velocity. Piston movement is generated from the power source expansion.

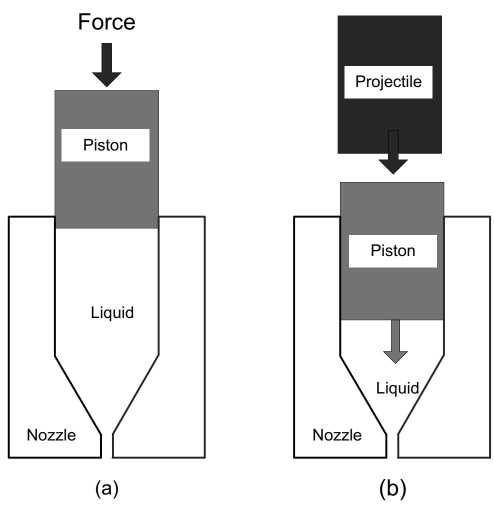

Figure 1. (a) Driving Object Method (DOM) and (b) Impact Driven Method (IDM)

This research proposes a new concept of the generation method of high speed liquid jet for jet injectors, i.e., the "impact driven method" (IDM) as Figure 1(b), which is expected to provide a more accurate timing and proper level of impact peak pressure at the early stage of penetration in the jet injector. Hence, better control, no back splash, and less pain should be accomplished. The prototype device is designed, assembled, and tested. Moreover, preliminary tests on the penetration mechanisms in polyacrylamide gels are visualized and compared with a commercial jet injector by using a high speed video camera.

Experimental Equipment

IDM jet injector

In this study, the prototype of an IDM jet injector is designed and constructed as shown in Figure 2 (a). The major task of the device is to generate wide ranges of high speed liquid jets. Jet velocities of approximately 340 m/s and impact peak pressures of approximately 38 MPa are expected. A liquid volume of approximately 0.2 mL and a nozzle orifice of 0.2 mm will be used.

Commercial jet injector: Cool click

A commercial jet injector named "Cool.click" used for delivering human growth hormone is selected as shown in Figure 2 (b). The purpose of testing this device is to compare the jet performance and behaviour between the IDM prototype and a DOM device. Cool.click works by the driving object method (DOM) and is currently widely used in applications. A liquid volume of approximately of 0.2 ml can be contained. The liquid contained in the nozzle is driven by a plunger-ram (driving rod), which increases the liquid pressure by direct compression, thereby accelerating the jet to a high efflux velocity. After the device is wound to energize the spring, the retained liquid is accelerated by a plunger-ram. This movement is generated from spring expansion when the trigger is pressed.

Motion analysis setup

To gain a better understanding of the dynamics of jet behaviors occurring during jet penetration, high-speed photography is performed (Photron APXRS motion analyzer). Liquid jets are ejected into 20% polyacrylamide gels (E=0.22 MPa), which was previously prepared. The gel is backlit with a white light source to allow the images to be captured at a frame rate of 10,000 fps.

The penetration mechanisms are determined in both the IDM jet injector and Cool.click. Both injectors are used with 0.2 mL of blue dye water in order to clearly distinguish the jet and the gel. Figure 2 (c) shows the visualization setup.

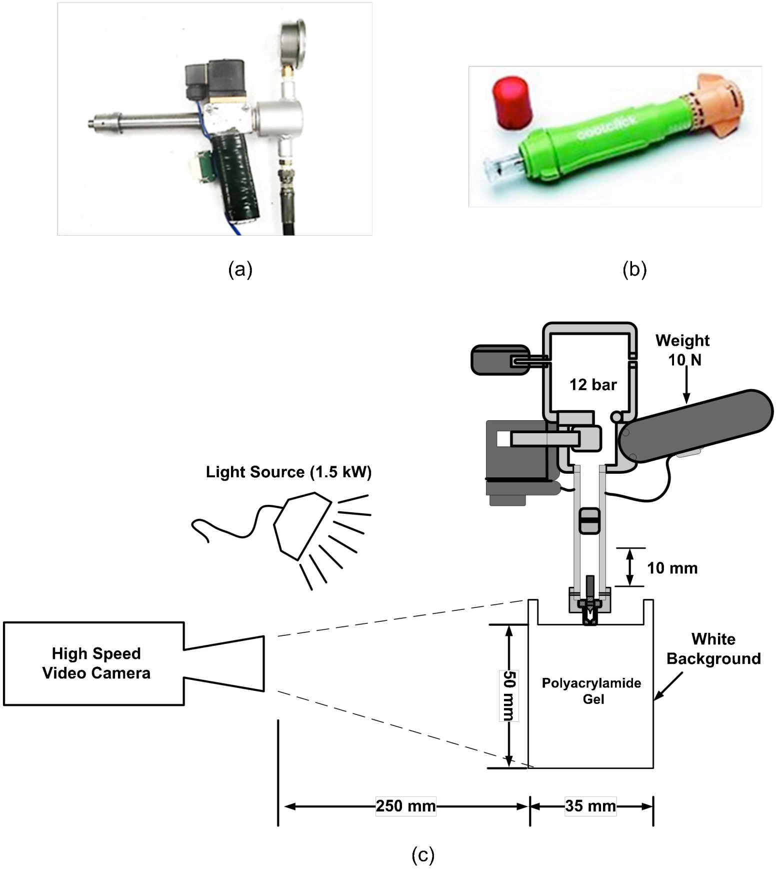

Figure 2. (a) IDM Jet Injector, (b) Cool.click, and (c) the visualization setup for determining the penetration mechanism

Results and Discussion

Penetration mechanism of IDM injector

First, for the IDM jet, the penetration stage is defined as the combination of the erosion and injection of the DOM jet. The shock wave in the nozzle obtained from the impact generates multiple pulsed jets. The first pulse takes care of the erosion task, and then the second pulsed jet is responsible for the injection. Because the erosion stage is designed to take a very short period compare to the entire delivery process, erosion can be neglected and the first stage can be called “penetration” for the IDM method. During the penetration, the first pulsed jet punctuates the first layer (i.e., first cavity) of the gel (as shown in Figure 3 at 1 ms). Then, the second pulse follows and causes a deeper penetration as a second cavity in the final target (at 3 ms). Later on, the penetration depth is reached as indicated by an unchanged depth, as shown in Figure 3 at 4 ms.This marks the end of the penetration stage.

The ejection stage starts to progress immediately after the end of penetration. The plunger pushes the liquid through the hole and reaches the final pocket, as shown in Figure 3 at 5 ms. At the pocket, the jet starts to accumulate and build up pressure to a certain level strong enough to crack or shear the gel tissue. Then, lateral dispersion starts, as shown in Figure 3 from 5-40 ms. In the IDM jet, when injection and dispersion occur concurrently, it is called the "ejection" stage.

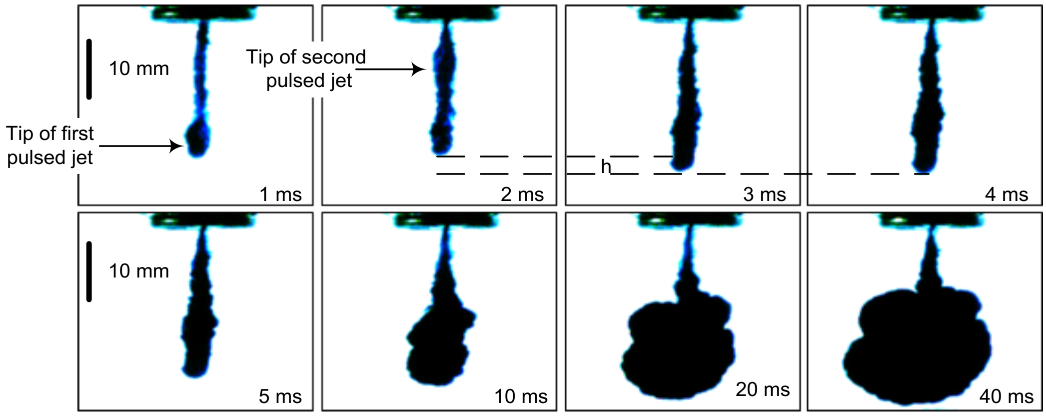

Figure 3. Delivery process from the IDM Jet Injector

Penetration mechanism of Cool.click

The stages of the delivery process of the DOM injector are presented in Figure 4. Three stages of injection can be noticed and are discussed here. The first stage is an "erosion stage," which is a really early stage where the liquid jet tries to pierce into the gel. Before piercing, some portion of the liquid is splashed back due to the lack of momentum of the jet tip to defeat the gel surface tension during the first 1-2 ms, as shown in Figure 4. Shortly, the main core jet is issued with sufficient momentum or impact pressure, and the jet can erode through the skin and start delivering the liquid jet into the target. This is called the "injection stage," as shown in Figure 4 from 3-5 ms. In this stage, a narrow hole can be observed while the liquid jet keeps penetrating into the target, and no sign of dispersion appears.

The last stage of the delivery process is the "dispersion" stage, where the penetrative depth is paused or slightly increased. The jet starts to expand horizontally and finally stops, as shown in Figure 4 from 5-40 ms. This stage normally takes a much longer time to complete compared to the "erosion and injection" stages.

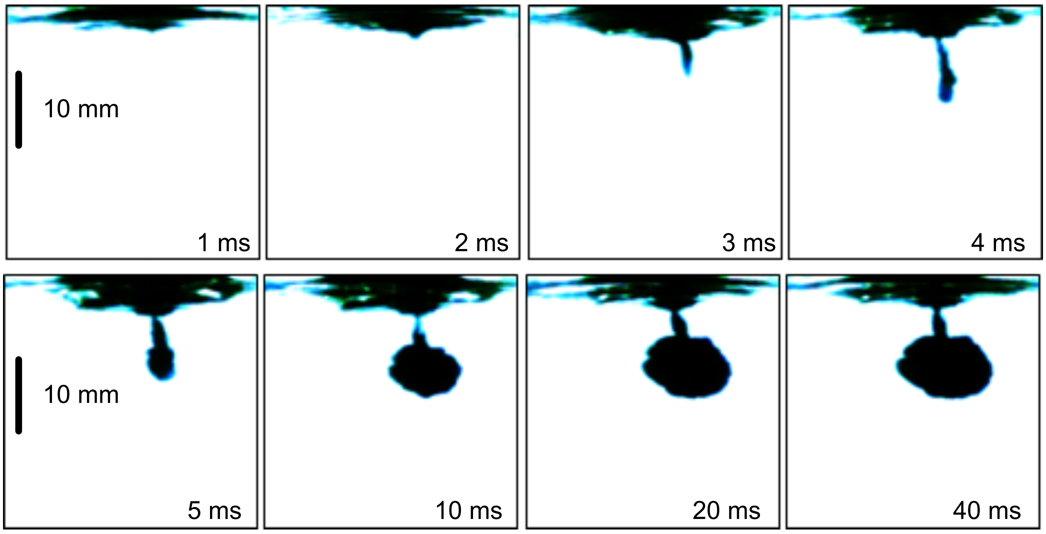

Figure 4. Delivery process of the DOM jet from Cool.click

In both jet injection principles, it is obvious that the mechanism of penetration and time in each stage are significantly different. The most different characteristic is found in the erosion stage. The IDM jet takes a very short time and has a high peak pressure, to overcome the threshold of erosion. Therefore, back splash is minimized, and the overall delivery efficiency will be improved. Additionally, the pain level and the possibility of infections are expected to decrease.

Figure 5 shows the top view area after the injection process. It is clearly observed that the IDM jet (Figure 5 (a)) has less back splash and better delivery efficiency. The good dispersion should provide a higher efficacy of the injection. Contradictory, with bad dispersion and some back splash, the drug may accumulate and diffuse to the target tissue too slow. Also, the patient may not receive enough dose of drug when some back splash occurs.

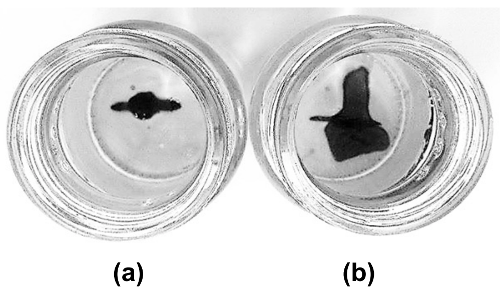

Figure 5. Top view area after injection: (a) IDM Jet Injector and (b) Cool.click

Concluding Remarks

The IDM jet gave a very short erosion period and thus can be neglected, while ejection and dispersion took place at the same time. Therefore, better lateral dispersion was achieved. Back splash or delivery efficiency was also checked, and it is found that the IDM jet provided very little back splash; hence, it exhibited higher delivery efficiency than the DOM injector. However, the control and accuracy of the IDM method still need to be carefully investigated and improved.

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