Validation of CFD simulation of recoilless EOD water cannon by firing experiments with high speed camera

Tonkid Chantrasmi*, Premsiri Hongthong and Manop Kongkaniti

Department of Mechanical and Aerospace Engineering, King Mongkut's University of Technology North Bangkok, Bangkok 10800, Thailand

* Corresponding Author: tonkid.c@eng.kmutnb.ac.th

Abstract. Water cannon used by Explosive Ordnance Disposal (EOD) were designed to propel a burst of water jet moving at high speed to target and disrupt an improvised explosive device (IED). The cannon could be mounted on a remotely controlled robot, so it is highly desirable for the cannon to be recoilless in order not to damage the robot after firing. In the previous work, a nonconventional design of the water cannon was conceived. The recoil was greatly reduced by backward sprays of water through a ring of slotted holes around the muzzle. This minimizes the need to manufacture new parts by utilizing all off-the-shelf components except the tailor-made muzzle. The design was then investigated numerically by a series of Computational Fluid Dynamics (CFD) simulations. In this work, high speed camera was employed in firing experiments to capture the motion of the water jet and the backward sprays. It was found that the experimental data agreed well with the simulation results in term of averaged exit velocities.

1. Introduction

Improvised Explosive Devices (IEDs) are a growing concern in many parts of the world including the southern part of Thailand. Many research and engineering works have been done to develop water cannon capable of defusing them by ejecting a high-pressure water jet to disrupt electronic circuits of the explosives before they can detonate. For additional safety, the water cannon can be mounted on a remotely controlled robot so that human operators are as far away from the dangerous areas as possible. It is highly desirable for the firing of the water cannon to be recoilless so as not to damage or immobilize the carrying robots. This allows the robots to be controlled back to the operation base, thus avoiding the need for the human operators to retrieve them from the dangerous area.

In our previous works [1-3], the authors proposed a design methodology to create a recoilless muzzle when other components of the water cannon were given. The method involved both firing experiments to quantify the given bullet driving force as well as a series of Computational Fluid Dynamics (CFD) simulations to find the operating point – i.e. the driving pressure and the water mass flow rate – of an actual firing [1-2]. In essence, the proposed methodology separated effects of the driving bullet from those of the muzzle design. In this way, a smallest number of actual firing tests were required and most work could be done through simulations by iterating on the designs of the muzzle alone.

The proposed methodology had been applied to a problem posed by Explosive Ordnance Disposal (EOD) division of the Royal Thai Army. From the existing off-the-shelves components, the .50 BMG bullets and water cannon barrel were given by EOD to the researchers who were asked to design a new muzzle that would reduce the recoil force. At the beginning of this research, a series of muzzle designs were tested and found that the recoil force could be reduced significantly [2]. Eventually, a recoilless design was found experimentally in a firing experiment (using some trend information from the previous simulations of older designs) [3]. Figure 1 shows this recoilless design, which featured 24 slotted holes with a certain shape around the muzzle. When fired, the cannon released backward sprays through these slotted holes to counterbalance the forward destructive water jet. The holes were at 45° angle with the main water jet velocity.

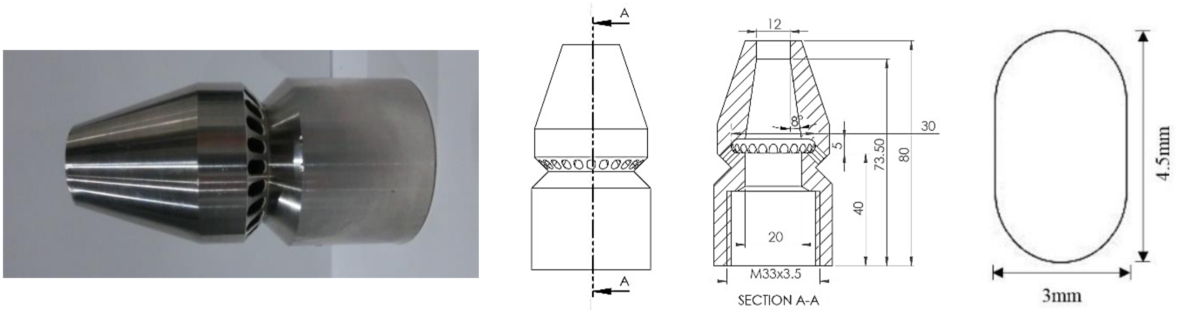


Figure 1. The current recoilless muzzle design.

Afterward, a series of CFD simulations of this recoilless design (to find the load curve) were carried out along with a detailed numerical study to find a set of optimal numerical parameters [4]. The simulations predicted that the water velocity at the main outlet was 501.5 m/s (using a steady-state simulation).

In this work, the authors describe a new firing experiment of the same water cannon and its result. A high-speed camera was deployed to capture the development of the water jet and the backward water sprays. In the next section, the setup of the firing experiment was described along with the remark on the recoil force or the lack thereof. Then, in the following section, the penetrated metal plates were shown and the destructive capability of the water cannon was discussed. Next, the results from high-speed recordings were analyzed and compared with the simulation results from the previous work in order to validate it. Finally, all aspects of the experimental results were summarized as the conclusion.

2. Experimental Setup and a Remark on the Recoil Force

Figure 2 shows the experimental setup with a high-speed camera in a military test-firing tunnel. The water cannon and the metal plate target were mounted on a metal frame with a wide base for stability. Both the cannon and the plate were at 45° angle with the leveled ground as shown. The main outlet of the muzzle and the middle of the metal plate were aligned along the direction of the water jet and they were 10 cm apart.

The target plate was firmly affixed to a mount at the end of a hollow rectangular tube, which is a part of the base, to allow the water to go through after penetrating the plate. Six hexagonal screws and a 1-cm-thick metal gasket with 10 cm inner diameter were used to hold the plate in place. On the other hand, the water cannon was free to slide upward along its rail since no fastening of any kind was used. The only forces kept it from doing so were its own weight and friction.

On the side of the base assembly, a high-speed camera was set at the same horizontal level as the muzzle with two additional stage lights for high-speed recordings. A clear acrylic screen was placed between the base assembly and the camera equipment for safety. The high-speed camera and the firing of the water cannon could be controlled remotely so that the researchers could operate them from outside the tunnel. It is worth noting that the acrylic screen turned out to be unnecessary in this case because the backward sprays dispersed as very small particles well before reaching the camera.

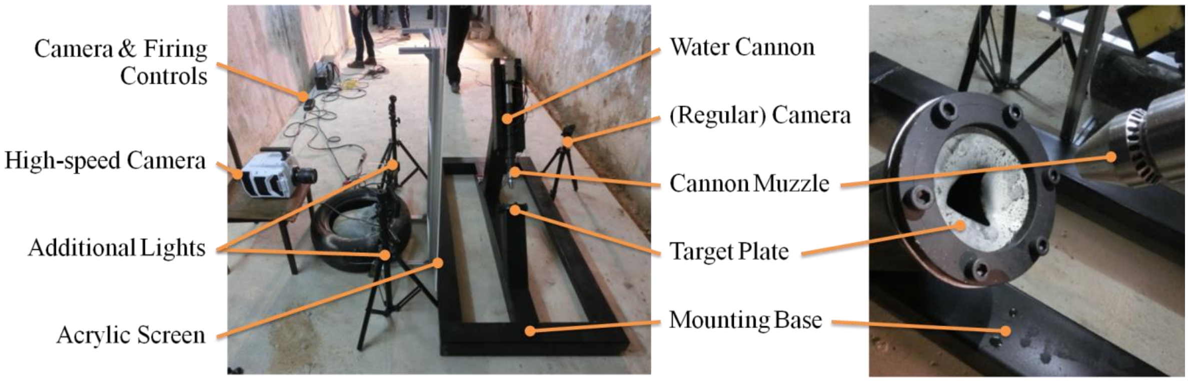


Figure 2. The experimental setup with a high-speed camera

The high-speed camera used was Phantom v2512 and the video recordings were done at 31 kfps for the first two firings and 39 kfps for the third firing.

In all video recordings, no movement of the muzzle could be detected at all. This validated that the firing of this water cannon was indeed recoilless or at least that the recoil was less than the amount of force required to slide the water cannon up (which could be easily done by an average person with one arm and could be estimated to be less than 200N).

3. Destructive Capability

Four metal (ST-41) plates were used as targets for the firings as described in the section above. The thickness ranged from 0.8 to 2.0 mm. Figure 3 shows the aftermath of each metal plate. The water jet was clearly capable of penetrating all the plates in the experiment. The size of the (water) bullet hole decreases as the plate thickness increases as expected.

(a) 0.8 mm thick

(b) 1.2 mm thick

(c) 1.6 mm thick

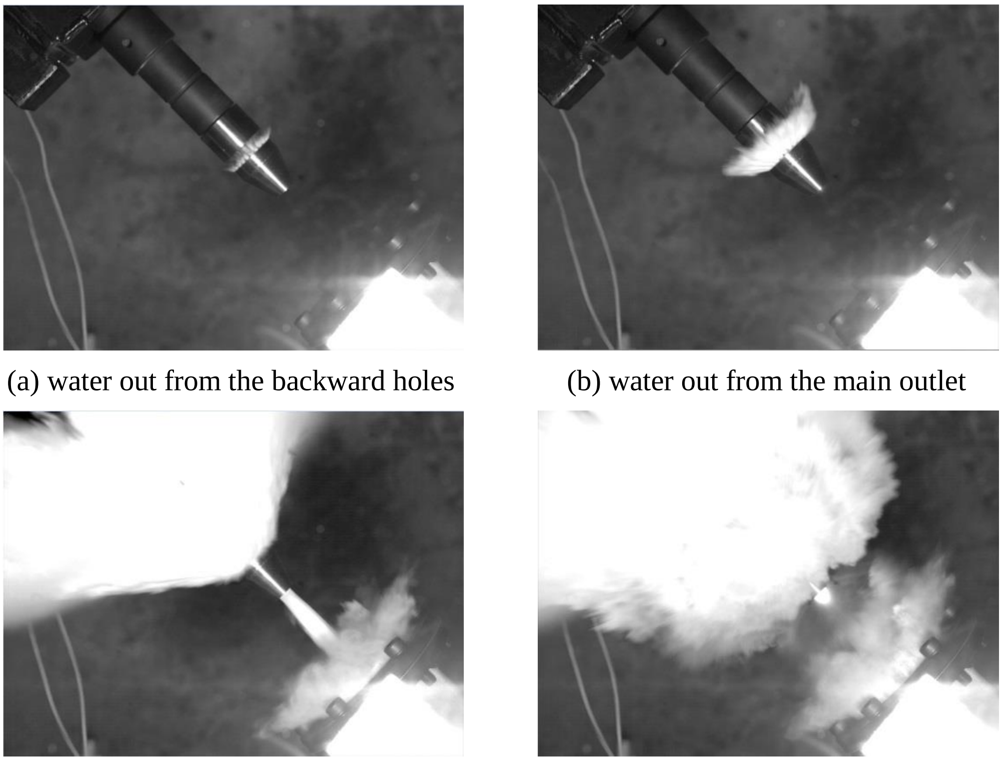
(d) 2.0 mm thick

Figure 3. The results of firing on target plates with different thicknesses.

4. High-speed Camera Results

Figure 4 shows four key frames from the video recording of the first firing. These four key frames were chronologically (a) when water started coming out of the backward holes, (b) when water started coming out of main outlet, (c) when the water impacted the metal plate target, and (d) when water inside the cannon was depleted. In the other firings, similar behaviors were observed in the same order but with variations in some quantitative measurements.

Before the evidence from high-speed recordings, it was unclear to the authors whether the water would be out of the main outlet or the backward holes first. A rubber stopper inside the muzzle was forcefully pressed against the main outlet on the inside as the high velocity water mass slammed into it. This caused the water to deflect backward to go out of the backward holes instead; however, eventually the rubber stopper had to be pushed out of the muzzle by the water pressure. It was unclear whether this would happen before or after some water came out of the backward holes. As it turned out in all firings in this experiment, the water came out of the backward holes approximately 0.2-0.3 ms before it did the main outlet. This small delay guaranteed that the recoil force was zero at all times during the firing as opposed to being damped over time.



(a) water out from the backward holes

(b) water out from the main outlet

(c) water impacting the target

(d) out of water

Figure 4. Key frames in development of the water flow during a firing.

All the video recordings were processed frame by frame to find the position of the leading edge of the main water jet in each frame. This was done by counting the pixels (via graphical software) and converted it into a physical length by using the known length of 8 cm of the muzzle as a reference. Figure 5 (left) shows the displacement of the leading edge of the water jet as a function of time from all the video recordings. The time was defined to be zero on the frame that some water was seen exiting the muzzle through the main outlet.

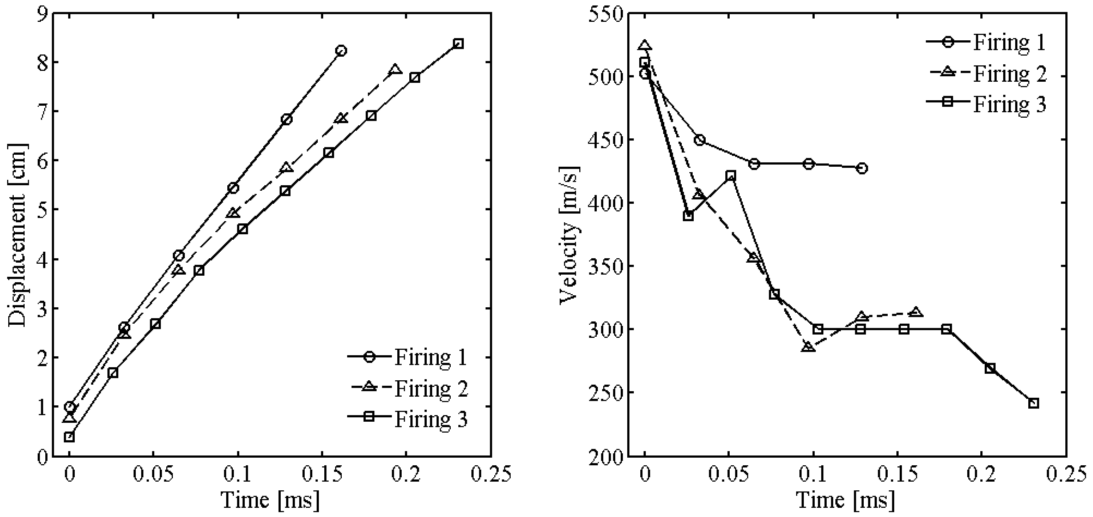


Figure 5. (Left) displacement and (right) velocity of the leading front of the water jet from the main outlet as a function of time from all three firings.

All firings show the same trend in the displacement, especially near the beginning of each firing. The discrepancy could be mainly due to the discrete time frames – the actual time when the water started to exit the main outlet could be anywhere between the two consecutive captured frames, but due to the limited captured frame rate it was locked down to the closest frame.

The first-order finite-difference approximation was used to estimate the velocity of the leading edge of the water jet from displacements of two consecutive frames and the known time interval between them. Figure 5 (right) shows this velocity approximation from all of the recordings. The authors would like to emphasize that this velocity by definition was the velocity of the leading edge of the water jet and *not* the velocity *at* the muzzle outlet. The two velocities were innately different because the aerodynamic drag force in the air slowed down the water jet that was out from the muzzle (and the cross-sectional area of the jet midair would be larger than the main outlet area). From the results shown in the above figure, the water could be reduced to as much as 50% of its speed at the muzzle outlet when it reached the target plate 10 mm away.

Fortunately, at the initial time as defined, the leading edge of the water was at the muzzle outlet. Therefore, the calculated velocity from the high-speed recordings at this point in time could be used to validate the velocity at the muzzle main outlet. Additionally, note that the initial velocities from firings were quite consistent. The average of these three velocities was 512.3 m/s, which was very close to the predicted result from the simulation of 501.5 m/s with a 2.1% relative error.

5. Conclusions

In summary, a firing experiment was setup and carried out to validate various aspects of the recoilless water cannon designed and manufactured in the previous works [3-4]. Metal plates of various thicknesses were used as a target to visually gauge the destructive force from the firing. A high-speed camera was setup to capture the development of the main water jet and the backward sprays. In all the firings, the water was shown to come out of the backward slots slightly before it did out of the main outlet. This transient behaviour ensured that the firings did not generate a recoil force from the very beginning as opposing to being able to damp it as time passed. The video recordings from 3 firings were processed to obtain an average water velocity at the main outlet.

From the experiment, three conclusions can be drawn: (1) the water cannon was confirmed to be *objectively* recoilless since the high-speed camera could not detect any movement of the cannon itself at all; (2) the firing of this water cannon was capable of penetrating a 2-mm-thick metal plate showing

IOP Conf. Series: Materials Science and Engineering **297** (2018) 012067 doi:10.1088/1757-899X/297/1/012067

a significant destructive force; and (3) the experiment validated the simulation results in term of the water velocity at the main outlet with a relative error of 2.1%.

Acknowledgment

This work is part of the research granted by Thailand Research Fund (TRF) entitled "Performance Evaluation of End Effectors of EOD Robot Prototype and Development of Training Curriculum for EOD Robot Operators," grant no. RDG5850117. The authors would like to thank Explosive Ordnance Disposal division of the Royal Thai Army for providing the testing facility as well as a number of water cannon components. The authors also greatly appreciate technical help from Hi-Tech Resources (Thai) Co.,Ltd. in setting up the high-speed recordings for this experiment.

References

[1] Tansuwannarat S 2013 *Numerical Analysis and Design of High-Speed Water Cannons to Reduce the Recoil Force Using Computational Fluid Dynamics and Experiments* (King Mongkut's University of Technology North Bangkok)
[2] Tansuwannarat S, Vallikul P and Chantrasmi T 2013 *Proc. The 4th TSME Int. Conf. on Mechanical Engineering (Pattaya, Thailand)*
[3] Chantrasmi T, Tansuwannarat S and Vallikul P 2015 *Proc. The 1st Asian Conf. on Dedence Technology (Hua Hin, Thailand)* (New York: IEEE)
[4] Hongthong P and Chantrasmi T 2017 *Proc. The 3rd Asian Conf. on Dedence Technology (Phuket, Thailand)* (New York: IEEE)