A Multidisciplinary Investigation of Medieval Flamethrowers: A Case Study

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Abstract - Multidisciplinary projects provide a unique opportunity to foster critical thinking in undergraduate engineering students and to help students develop an understanding of the design process. These types of projects can also motivate student interest in the engineering design process. In this paper, the authors will present a case study of one such interdisciplinary project, which combined engineering analysis and a study of technological history, conducted by an undergraduate mechanical engineering student. The student investigated three different designs for a hand-held flamethrower that projected a highly flammable liquid, known as Greek fire.

For this project, a student used historical accounts to design, construct, and test each of three flamethrower designs to determine the feasible operation for each. This work concentrated on the student's ascertaining the similarities and differences between the three designs and on the student's developing effective operating and valve systems. The original project was to investigate Chinese and Byzantine designs, but during the project, information in the Arab design was obtained and that design was also constructed by the student. [Englehart, 3]

Keywords: Flamethrower, Byzantine, Chinese, Arab, medieval.

Introduction

Warfare in the Byzantine Empire between the 7th and 11th centuries CE saw the development of weapons systems using fire. Partially responsible for this revolution in weapons was the creation of a highly flammable liquid by the Syrian architect Callinicos in 7th century CE. [Davidson, 2] This was known as liquid fire, later referred to as Greek fire. Greek fire was utilized in one particularly effective weapon, the flamethrower. Large flamethrowers were mounted on naval vessels and sprayed enemy vessels with flaming liquid. There are few historical accounts written by the Byzantines or others describing their weapon, likely due to attempts to keep the design a secret.

A hand-held flamethrower was also developed. The hand-held version of the flamethrower was capable of projecting a stream of fluid for a short distance. Around 900 CE the Chinese seemingly used the Byzantine design, at least in principle. They documented the weapon, drawing basic diagrams and providing descriptive narrative of their version of the flamethrower's design which appears in the *Wu Ching Tsung Yao*, or the *Collection of the most Important Military Techniques*, written in the early 11th century. [Needham, 7] The Arabs developed a hand-held flamethrower along the same lines as the Byzantine and their version is shown in the *Elegant Book of Trebuchets* with little narrative. [Nicolle, 9]

All of these flamethrowers were seemingly designed using the principle of a double-action pump. The function of a double-action pump is to produce a continuous stream of liquid by use of two chambers separated by a piston. While one chamber is compressed by a piston and forces the fluid out, the other chamber expands and creates a partial vacuum which draws the fluid in. When the piston changes direction, the chamber previously in compression begins to expand and becomes a partial vacuum and the fluid is forced out the other way. Each chamber needs an outlet valve which opens and closes alternately while valves control the fuel inlets in opposition. Double-action pumps were broadly used throughout antiquity in many forms. Ctesibius of Alexandria is attributed with the

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development of a double-action liquid pump in the 2nd century BCE. The Chinese have an account in which a device similar to a box bellow was used to fumigate enemy tunnels during a siege. Similar apparatuses appear in forges in the form of both box- and skin-bellows. [Needham, 7] The objective of this research was to investigate the various uses of double-action pumps in ancient weaponry in the form of continuous stream flamethrowers.

The Byzantine Flamethrower

The initial flamethrowers used by the Byzantine military were mounted on naval vessels. These flamethrowers consisted of a large cauldron containing Greek fire which was heated by fire and pressurized by a pump. As illustrated in Figure 1 [Haldon, 5], the pressure buildup inside of the cauldron would force the liquid through a tube, which Partington describes by paraphrasing King Leo VI:

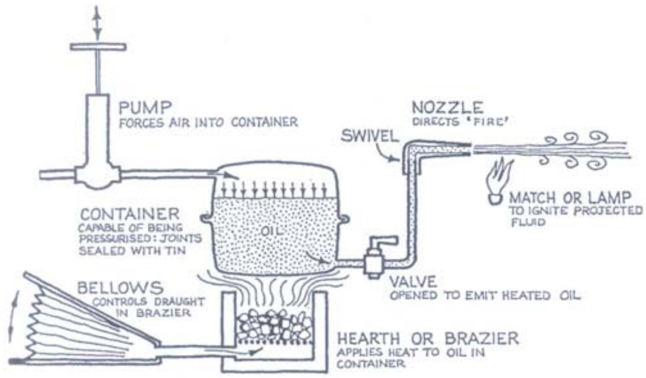

Figure 1: Shipboard Byzantine Flamethrower

> "The front part of the ship had a bronze tube so arranged that the prepared fire could be projected forward to left or right and also made to fall from above. This tube was mounted on a false floor above the deck on which the specialist troops were accommodated and so raised above the attacking forces assembled in the prow. The fire was thrown either on the enemy's ships or in the faces of the attacking troops." [Partington, 10]

Not only were these flamethrowers capable of covering enemy vessels in fire, but the liquid itself, Greek fire, was difficult to extinguish once ignited.[Partington, 10] Although the Byzantines relied mostly on these larger flamethrowers as a naval weapon, smaller hand-held pumps were also developed and used in close combat. The use of Greek fire was reportedly rarely used on land. [Roland, 11] When Greek fire was used, one of the devices which employing the flammable liquid was the hand-held, double-action pump flamethrower. The design was never documented and accounts of its existence are few. Heron of Byzantium mentions the use of this weapon briefly in the *Parangelmata Poliorcetica* while instructing in the use of a drop-bridge.

> "And if some of those standing on the cross-bridge also use a swivel tube, handheld incendiaries to shoot fire in the direction of the enemy …." [Sullivan, 12]

Along with this description, Heron adds a drawing of a soldier standing atop one of these cross-bridges while wielding one of these hand-held flamethrowers. This drawing of the flamethrower also happens to be the only historical depiction of the weapon as shown in Figure 2 [Sullivan, 12]. The picture does not show how the fluid mixture was ignited. A slow burning match could have been affixed to the exit chamber. The slow burning match could be soaked in saltpeter as was used in later forms of artillery and hand weapons.

The Chinese Flamethrower

The Byzantine flamethrower pre-dates the earliest known Chinese version by at least 300 years. However, the technology of a double-action pump was not new to the Chinese. Needham states there is a reference in the book on military technology written by Mo Tzu to what seems to be a double-action type pump as early as the late 4th Century BCE in which the Chinese used a pump that relied on a pushing and pulling motion. [Needham, 7]

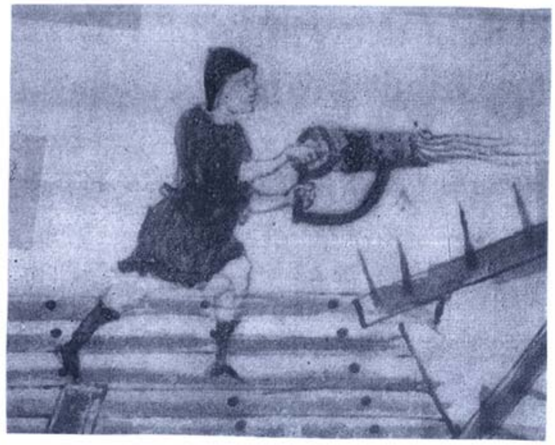

Figure 2 Byzantine soldier with a handheld

Although the Chinese had the technology of the double-action pump, the flamethrower was still not described until the 11th century CE. One of the earliest accounts of this type of flamethrower in China comes in a story from the *Ching Hsiang Tsa Chi* (10th century CE) in which Needham says "…certain officials were laughed at for being more expert with it than with their writing-brushes." This flamethrower, unlike the Byzantine version, was documented and illustrated in the *Wu Ching Tsung Yao* (*Collection of the most important Military Technique).* [Needham, 6] The narrative gives a description of the flamethrower which details its design,function, dimensions, how to load, operate, clean, and use. Needham provides the translation and diagram (Figure 3) [Needham, 8].

> In the *Wu Ching Tsung Ya,*the device depicted in Figure 3 is described as: "On the right is the naphtha flamethrower. The tank is made of brass, and supported on four legs. From its upper surface arise four (vertical) tubes attached to a horizontal cylinder above; they are all connected with the tank. The head and tail of the cylinder are large, (the middle) is of narrow (diameter). In the tail end there is a small opening as big as a millet-grain. The head end has (two) round openings 1 ½ in. in diameter. At the side of the tank there is a hole with a (little) tube which is used for filling and this is fitted with a cover. Inside the cylinder there is a (piston-) rod packed with silk floss, the head of which is wound round with hemp waste about ½ in. thick. Before and behind, the two communicating tubes are (alternately) occluded, and (the mechanism) thus determined. The tail has a horizontal handle (the pump handle), in front of which there is a round cover. When (the handle is pushed) in (the pistons) close the mouths of the tubes (in turn)."

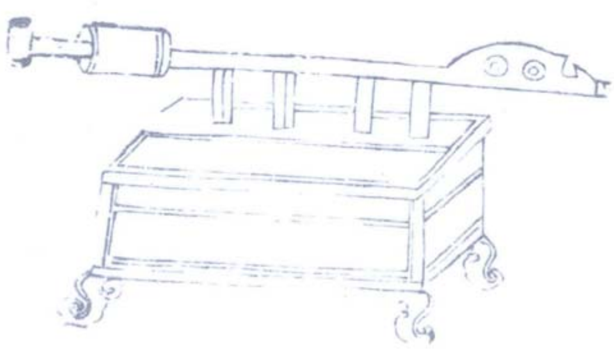

Figure 3 Chinese flame thrower

> "Before use the tank is filled with rather more than three catties of oil with a spoon through a filter; at the same time gunpowder (composition) is placed in the ignition-chamber at the head. When the fire is to be started one applies a heated branding-iron (to the ignition-chamber), and the piston-rod is forced fully into the cylinder – then the man at the back is ordered to draw the piston-rod fully backwards and work it (back and forth) as vigorously as possible. Whereupon the oil (the naphtha) comes out through the ignition-chamber and is shot forth as blazing flame.
>
> "When filling, use the bowl, the spoon and the filter; for igniting there is a branding-iron; for maintaining (or renewing) the fire there is the container. The branding-iron is made sharp like an awl so that it may be used to unblock the tubes if they get stopped up. There are tongs with which to pick up the glowing fire, and there is a soldering-iron for stopping-up leaks." [Needham, 6]

Although this does not describe the inner-workings of the flamethrower, it gives a clear description of what is to occur while the weapon is being operated. From this, Needham attempted to diagram what he thought was the internal configuration of the weapon. However, in building this version of the flamethrower, it is became apparent by following the Chinese diagram, the flamethrower would operate as Needham surmises, but the geometry is not correct.

Needham's design shows the four tubes all connected with the tank, two of which act as siphoning tubes. He shows that there are two pistons, which effectively act as one, "…possibly for greater rigidity."

Needham's design, Figure 4 [Needham, 6], shows that when the piston-rod is pressed all the way forward, the hole for the rear siphon tube is cleared while at the same time the forward hole is occluded. When the piston-rod is pulled completely to the rear, the rear hole is occluded and the front hole cleared. He shows a tube which connects the rear chamber to the nozzle, and the connection is made inside the tank. This gives the weapon the appearance of four vertical tubes running down into the tank, as the original Chinese diagrams show, while at the same time hiding the connection between the rear tank and nozzle, which is one of its key features for functioning correctly.

The ignition chamber of the Chinese version is unique. The diagram shows it as being semi-circular in shape and having two holes on the side, which likely functioned as loading holes for the gunpowder in the ignition chamber and where the branding-iron could be stuck to ignite the gunpowder. The fluid from the weapon would be shot from the nozzle through this ignition chamber and, while streaming through, would catch fire from the burning gunpowder.

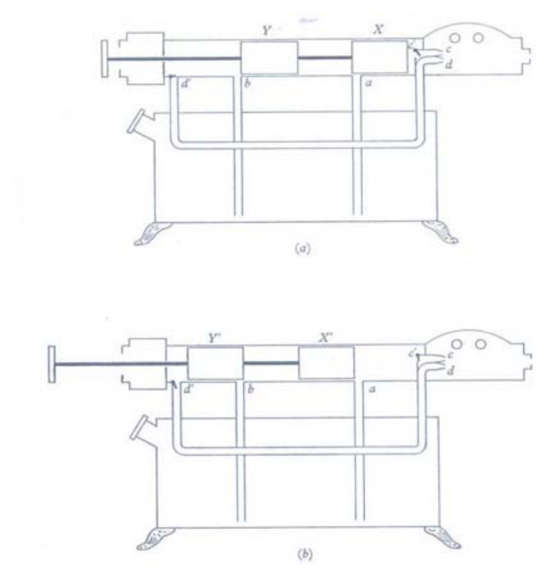

Figure 4 Needham's proposed solution to the Chinese flame thrower

The Arabic Flamethrower

The Arabic flamethrower seems to follow the Byzantine design but the geometry has become convoluted since the return tube of the Byzantine design is now an enclosing concentric return with the fuel tank separate from the pump tube. The design for this is shown in the *Kitâb aniq fî'al-Manâjanîq* (*Elegant Book of Trebuchets)* [Ibn Aranbughâ al-Zaradkâsh, 6] and shown more clearly by Nicolle [Nicolle, 9], shown as Figure 5.

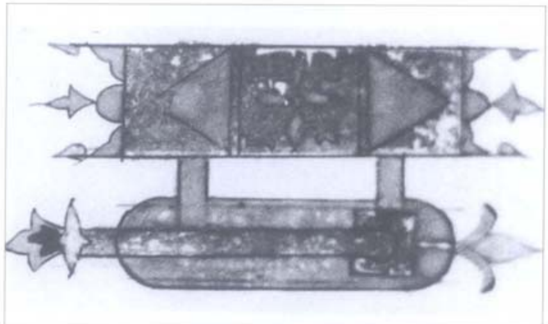

Figure 5 Arabic Flamethrower

About the only thing mentioned in the *Elegant Book of Trebuchets* is that there was a fuel tank with a copper shooting siphon beneath the fuel tank. [Nicolle, 9] From this source, we do not know how the flammable fluid was ignited. We may surmise that perhaps a slow burning match was tied to the forward projecting tube.

Student Design Solutions

Chinese Design Solution

This project began with the student analyzing the Chinese design as it is the flamethrower with the best technical information readily available. The best diagram of the Chinese device is shown in Figure 6. For the Chinese system, the device remained consistent with Needham for the use of the connecting tube within the tank, however the design used diverged from Needham's idea of the two separate pistons moving together, seen in Figure 6 [Needham, 7].

The student found that there just is not sufficient space within the piston tube if the diagram's relative dimensions are to be used. Therefore, in his design the student placed a stationary rear piston at the back of the device, to seal and support the pump-rod. If the "…hole the size of a millet grain" [Needham, 6] referred to the hole in which the pump-rod passed through the tail end, this would result in a small diameter, rod rendering the pump-rod flexible and, perhaps, weak. The student's rear stationary piston design resulted in better agreement with the diagrams.

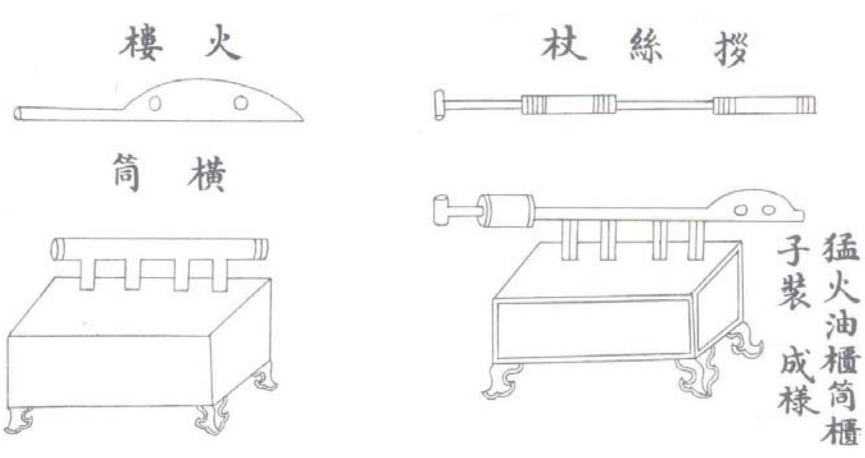

Figure 6 Components of the Chinese Flamethrower (Fierce Fire Oil Projector)

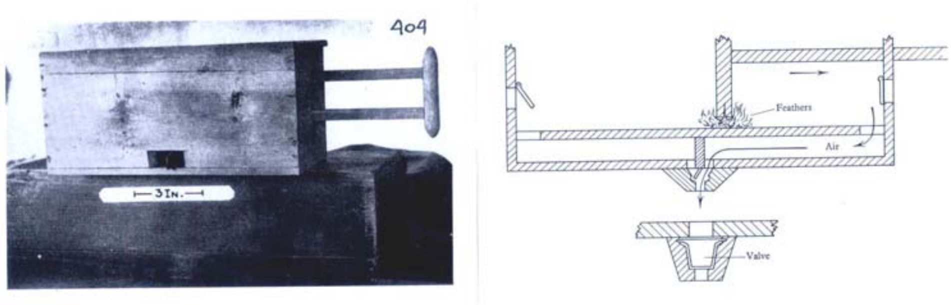

Figure 7 Chinese Box Bellows

The Chinese box bellows noted in the introduction is shown in Figure 7. [Needham, 7] The box bellows has a single rigid flap valve that acts for both outlet valves and the piston could take the place of opening and closing the inlet valves. Figure 8 shows a generalized version of what is needed. When the piston was pressed forward, the rear inlet would clear about halfway through the stroke, meaning the initial vacuum created in the chamber would draw an initial amount of fluid into the chamber and during the rest of the stroke more fluid would be drawn in. The same operation would apply when the direction of the piston's motion was reversed.

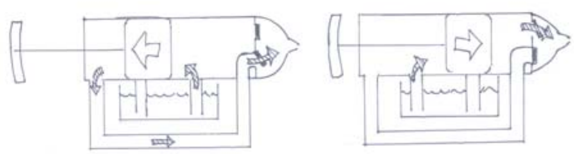

Figure 8 Generalized Flamethrower

The design employed by the student for the flamethrower started with the tank. In the description, the tank is to be filled with "…rather more than three catties." Three catties is about 91.5 in.^{3} (1500 cm^3) of fluid [Guralink, 4] and therefore the tank was to be able to contain more according to the description. Given the dimensions of the tubes and using ratios from the diagrams, the student designed the tank to be 16 in. (40.6 cm) long, 6 in. (15.2 cm) wide and 4 in. (10.2 cm) tall. This provides more than enough volume for three catties.

The four vertical tubes used by the student in his design are spaced such that the two rear tubes are 3 in. (7.62cm) from center to center, the two middle tubes are 4 in. (10.16cm), and the forward two tubes are again 3 in. (7.62cm) apart. The overall length of the piston chamber is 15 in. (38.1 cm) which the student setermined from the diagram showing the chamber to be approximately the same length as the tank.

The pistons are each 5 in. (12.7cm) long. On the rear part of the piston chamber a larger diameter short length tube was mounted by the student, likely to catch any of the fluid which leaked out of the pump-rod hole. The main piston tube was made by the student from 1 in. PVC pipe, the verticals were made of ¾ in. (20 mm) PVC and the rear larger cylinder was made from 1 ½ in. (38 mm) PVC. The fuel tank was made from plywood with a Plexiglas top. Figure 9 shows a diagram of the Chinese device designed by the student and Figure 10 shows a photograph, of the device constructed by the student.

Byzantine Design Solution

The drawing in Figure 2 [Sullivan, 12] depicts this weapon to be a tube with a diameter approximately one-third of its length and a handle projecting from the bottom with what appears to be a hose connecting the rear bottom to the front of the larger-diameter tube. The soldier depicted in Figure 2 is holding the handle on the bottom tube of the device with his left hand while working what was possibly the pump-handle with his right.

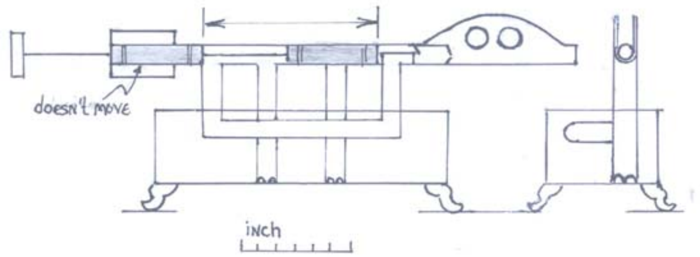

Figure 9 Chinese Flamethrower - Design Solution

Figure 10 Chinese flamethrower - as Built

In order for the weapon to have the capability of operating fairly continuously, the student determined that the pump would have to be double-acting. Many student and mentor discussions of the possibilities of the weapon's design took place. They concluded that the most reasonable configuration of the weapon was that the large outer tube made up the reservoir for the flammable liquid. Inside of this large outer tube is a tube smaller in diameter which housed the double-action pump. The handle and hose, which connect the bottom of the handle to the front of the device, provided a path for the liquid forced through the back chamber of the pump to the nozzle. Attached to the middle of the inner piston tube is another small tube which extends to the bottom of the reservoir and functions as the inlet siphon for the liquid into the pump.

Through his research, the student found that, like the Chinese device, the Byzantine version is believed to have only two values, located at the exit chamber immediately behind the nozzle. The valves at the exit chamber close when its relative chamber is in the expansion stage and open during compression. The piston acted as the other two valves by closing off the fuel inlet immediately during the compression stroke and opens the fuel inlet at the end of the expansion stroke; doing this in both directions.

To operate the weapon, the student assumed that the piston-rod handle was pushed forward. This would force any liquid in the forward chamber into the exit chamber and out of the nozzle while simultaneously the piston occluded the inlet, and due to the one-way valve covering the outlet at the exit chamber, created a partial vacuum in the rear chamber. Once the piston cleared the inlet tube, air pressure forced the liquid through the inlet and into the rear chamber. At this point the direction of the piston was pulled back which forced the liquid in the rear chamber through the tube running forward to the exit chamber, through its one-way valve and out of the nozzle. Simultaneously the one-way valve for the forward chamber, located at the exit chamber, closes creating a partial vacuum. Once the piston cleared the inlet tube, pressure forced the liquid into the empty forward chamber. Continuous back and forth action created a nearly continuous stream of fluid through the nozzle. The stream was only briefly cut between strokes due to the change in direction of the piston and delay in opening the occluded inlet tubes.

The dimensions of the flamethrower were determined by the student from a picture which accompanied Heron of Byzantium's instructions of use of the siege ladder. The student assumed that the average man at the time was approximately 5 1/2 ft (168 cm) tall. From the picture and height assumption, the student formed a scaling ratio upon which he based the dimensions of the flamethrower. The outer reservoir came out to be about 13 in. (33 cm) long with a diameter of approximately 4 in. (10.2 cm) in diameter. The handle came out to be approximately 4 in (10.2 cm) long with a diameter of about 0.5 in (1.3 cm). The inner diameter of the pump was decided by the student to be approximately 1 in. (2.5 cm). From these dimensions the device was constructed by the student using PVC piping of the closest dimensions.

The student tested the operation of his constructed flamethrower and found that his design worked. The partial vacuum was capable of drawing the liquid into the chambers, filling them enabling the mechanism to function properly.

Overall, this design, which would have been conceivable and producible with the technology and science of the time, was possibly the design used for the Byzantine flamethrowers. Not only does it function properly, it also matches the description of its function and resembles the device in the historical drawing. The clues to its construction and operation were deduced from the Chinese version which was historically documented in writing and diagrams. A drawing of the student's design is shown in Figure 11, and a photograph of the device constructed by the student, based on his design, is presented in Figure 12.

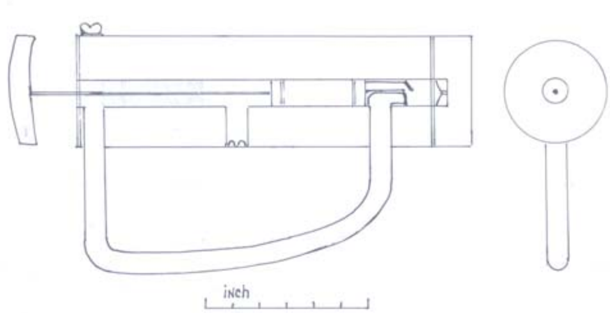

Figure 11 Byzantine Flamethrower – Design Solution

Figure 12 Byzantine flamethrower - as Built

Arabic Design Solution
Only a picture of the Arab device was available to the student. The fuel tank is above the siphon as stated in the previous section on the Arab device, as shown in Figure 5. The design for the Arab device was again presumed by the student to use only the two forward valves and used the piston to occlude the inlet tubes. It appears from the diagram that a tube was down the middle of the siphon into which the piston with its handle was inserted. Since there was no tube running from the back to the exit chambers, the student assumed that the outer cylinder constituted the return. The forward end of the piston cylinder would have had a hole in the bottom. To allow for a return the student designed the flamethrower so that the rear of the piston cylinder was supported by a square as shown in Figure 5. A drawing of the student's design is shown in Figure 14 and a photograph of the device constructed by the student, based on his design, is shown in Figure 15.

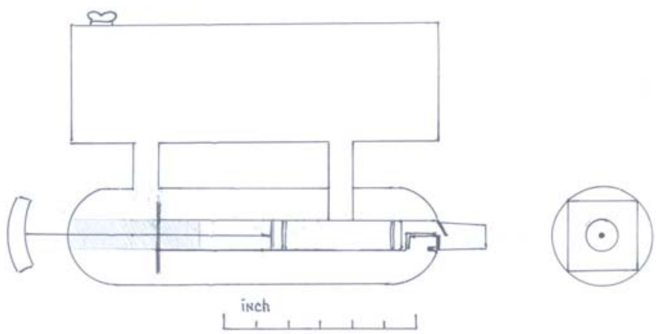

Figure 13 Arab flamethrower - Design Solution

Figure 14 Arab Flamethrower - as Built

Valves
Through his historical research, the student found that none of the sources mention or hint at the type of valves used in these devices. The student determined that the simplest type of valve to use was flap valves, which have been used in air and fluid pumps for centuries. A common valve still in use today is the one way valve, in the blowpipe, used to supply air to the class of musical instruments known as bagpipes.[Baines, 1] The student developed two ideas utilizing the flap valve, as shown in Figures 15. He found that both of these worked. The flap valves were made of leather. Since he located the outlet holes one above the other, using a single rigid horizontal flap created problems with closing. Although he used aluminum to form the body of the valves, he felt that a wooden cylinder would have worked as well and should probably have been the material used. However, there was not sufficient time for him to test this.

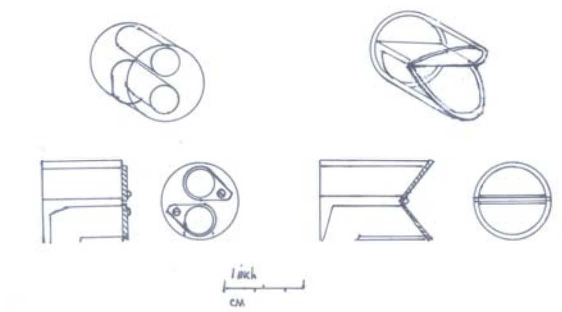

Figure 15 Front Valves

Project Conclusions
Through his work with this project, the student concluded that the three cultures apparently communicated the general design of the flamethrower. The original design seems to have been the Byzantine model, then to China and back to Arabia. He found it interesting that each device uses the same operating principle but appear to be different only because they vary geometrically. Through his testing of each of his three designs, he found that all three designs project fluid about twenty feet in a slightly intermittent stream. He determined that the stream is slightly intermittent because the piston replaces two of the valves which do not cover the inlets completely during the forward and back motion. Therefore, the device must be pumped rapidly back and forth to compensate for this. The student used water as the fluid to be pumped because of safety concerns. However, he recognized that different fluids could affect the operation of the devices.

Conclusion

Through his work with this multidisciplinary project, the student gained critical thinking skills, since much of the actual design of these flamethrowers had to be reverse engineered due to the lack of detailed historical accounts. Almost all of the useful information came from the Chinese accounts and drawings. The student also gained a better understanding of the design process by having to use CAD programs, various machine shop machines and tools, and also by having to develop appropriate testing of mechanical performance. Perhaps, more importantly, through this multidisciplinary project, the student gained a greater interest in engineering design and its applications.

References

[1] Baines, Anthony, *Bagpipes*, Information Press Ltd, Oxford UK, 1995

[2] Davidson, H.R. Ellis, ”The Secret Weapon of Byzantium”, *Byzantinische Zeitschrift*, 66, No.1,1973, 62.

[3] Englehart, Matthew J., Ancient Byzantine and Chinese Flamethrowers, Summer Undergraduate Research Institute, Virginia Military Institute, 2008.

[4] Guralink, D.B., *Webster’s New World Dictionary of the American Language*, Collins Publishers, Inc., 1979.

[5] Haldon, J., “A Possible Solution to the Problem of Greek Fire”, *Byzantinische Zeitschrift*, 70, no. 1, 1977, 91-99.

[6] Ibn Aranbughâ al-Zaradkâsh *Kitâb anîq fî’al-Manâjanîq*, Topkapi Library, Ms. Ahmed III 3469, Istanbul,1462.

[7] Needham, Joseph. *Science and Civilisation in China.* vol. 4, part 2, section 27, Cambridge: Cambridge University Press, 1965, 137-148

[8] Needham, Joseph. *Science and Civilisation in China.* Vol. 5, part 7, section 30 continued, Cambridge: Cambridge University Press, 1986, 91.

[9] Nicolle, Davis, *Medieval Siege Weapons (2), Byzantium, the Islamic World & India 476-1526*, Osprey Publishing, 2003, 37.

[10] Partington, J.R. *A History of Greek Fire and Gunpowder.* Baltimore, MD: The Johns Hopkins University Press, 1999, 3,18.

[11] Roland, Alex. "Secrecy, Technology, and War: Greek Fire and the Defense of Byzantium, 678-1204”, *Technology and Culture* (University of Chicago Press) 33, no. 4, 1992, 655-679.

[12] Sullivan, Denis F. *SIEGECRAFT TwoTenth Century Instructional Manuals by "Heron of Byzantium".* Washington, D.C., Dumbarton Oaks, 2000, 99, 305

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