# A Continuous–Flow Steam Generator for a Cookstove

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FORWARD

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A number of people have proposed using a jet of high speed gas (steam or air) to stir up the flue gasses in a wood burning cookstove, so as to increase mixing, improve combustion, and reduce pollutants. The benefits are similar to adding a fan to a stove, but with less complexity and no need for electricity. Systems that I've seen in the past are batch systems that have a number of drawbacks. This report covers a continuous flow steam injector which I believe is much better. It was designed by a group of mechanical engineering students, with a few suggestions from me. The advantages of this system over previous batch flow systems are that this system runs continuously without being refilled, is controllable in terms of how much steam is being injected, and can not overpressurize as long as the valve is open.

The bulk of this document is a report done by the students for their senior design and experimentation class in the Mechanical Engineering Department at the Ohio State

University. The instructor, Prof. Dennis Guenther, is my co-worker, and the origin of this project was when he asked me for ideas for student projects. The work was done in the winter and spring quarters, 2007.

The scope of this project included developing a means to generate a high velocity jet of steam with a mass flowrate of less than or equal to 0.2 g/sec (which would take about 500 W of heat from the fire). They succeeded in doing this in a controllable simple system that can vary the steam flow from much less than 0.2 g/sec to much more than 0.2 g/sec. The scope of the project did not include figuring out what is the optimum amount of steam to produce, nor how to best utilize the jet of steam, since these are specific to the design of the remainder of the stove.

The report given here should be taken as a starting point. In my opinion it presents a good basic idea that can be taken and developed in more detail by others, possibly with significant changes. I believe the system could be made much simpler and less expensively than the students imply. A better quantitative analysis could be done using simple tools and techniques.

The report was written as part of the requirements of the class, and is therefore written in the style of a class report rather than in the style of a technical paper.

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**Abstract**

In developing nations of the world a common means of food preparation is through the use of biomass fueled cook stoves. Regardless of the efficiency or lack there of, these stoves are an only option for many of their users. It has been noted that these stoves pose a degree of physical harm to those around them. The goal of this particular project has been to implement a steam injector system onto one of these stoves in an effort to stir combustion gases within the stove.

An injector system has been designed, constructed, and tested. Concluded results have pointed to a successful creation of a unit that uses a small amount of water to produce a steam jet in the stove which stirs the flu gases. This system is simple, effective, and above all safe. It is hoped that this system can be implemented so as to create a safer environment for those who interact with biomass cook stoves.

**Introduction**

Biomass stoves are found mostly in developing countries, and negative health effects swarm around them. The high volume of smoke they produce and the pollutants contained within that smoke are a major health risk for their users. According to the World Health Organization, indoor air pollution is to blame for 1.5 million premature deaths and 2.7% of the global burden of disease. However, there is potential to pursue solutions to help alleviate some of these pollution concerns.

<u>For this particular endeavor, a problem statement was created as follows:</u>

*In the developing world, wood and charcoal stoves are used for cooking. These stoves produce a large amount of smoke and Carbon Monoxide. To reduce pollutants, create a device for injection of a high speed jet of air or steam. The goal is develop a way of boiling water with low pressure levels. The device shall be simple and inexpensive.*

This is not the first attempt to create a system that has these goals. Other work has been done and there has been success to a degree. The most effective existing design is a Chinese device that functions somewhat like a tea kettle. This device is filled with water and placed directly in the stove. The stove's heat will eventually boil the water contained within the metal device and will jet steam into the combustion chamber. A device similar to the one described here is shown in Figure 1.

The Chinese design is effective at creating a steam jet that stirs the combustion gases. However, there are a few drawbacks to a system like this. First, by placing all the water into the combustion chamber a large amount of the stove's energy will go into heating that water. Also, capacity limitations require that the device be refilled several times every hour.

**Design Focus**

From the initial start of the project, the group used a basic approach to design. Brainstorming through the use of figures and diagrams to show concepts were sketched into notebooks. A consensus was drawn on the approach to take and a preliminary idea was sketched. The primary focus when first starting the project was an inexpensive apparatus completely self contained. No external reservoirs, electrical switches, or timers/counters would be needed to operate the apparatus. By making the apparatus self-contained, in turn, the assembly would be simple and minimal.

Although there were setbacks to the initial design, the concept did not change until the very end. Small changes were made in each design revision, but an attached reservoir was used throughout. The method of attachment to the reservoir varied as the design became more refined.

Focus shifted towards a working mechanism the latter half of the project. Although an inexpensive apparatus was still a primary focus in the final design, a working mechanism with flow rate data took priority. The main problems with the initial prototype was flooding of the system, infrequent boiling, water leakage, top heavy weight, low steam injection pressure and velocity. Through careful analysis the problems were eliminated one by one. The entire apparatus was sealed with pipe dope and thread joint tape. A complete redesign of the water reservoir by detaching and elevating it resolved more issues. Finally, a decrease in flow area and a change in valve type reduced the water flow enough for an instant boiling.

Now that a working mechanism with consistent results was present, focus shifted towards data analysis. A flow rate goal was set and various valve positions were tested to determine the optimum operating angle. Careful study was given to safety concerns regarding back pressure and exit velocity. The current design implemented throughout the world has the tendency to clog. With a valve set to a specific location, the apparatus can be left alone and will not build enough pressure to explode. With a flame directly on the elbow, the water will extinguish the heat if the exit hole clogs. This safety feature also works after the stove is turned off; the water flowing into the reservoir can be increased to cool the pipe fittings. More on the details of design will be given later in this report.

**Initial Prototype**

The first constructed system can be seen in Figure 2. It was tested and had some success. The majority of the design was constructed of ½" steel piping, and was fitted with a ½" ball valve that was mounted just below the reservoir so as to control the flow rate. The boiler for this design can be seen in Figure 3. The boiler itself was six inches long and had three ejector nozzles. These ejector nozzles were each 0.0625" in diameter, and were offset ½" vertically and 45° angularly.

When tested, this design worked, but only for a period of roughly 5 minutes before the ejector nozzles began to emit liquid water streams onto the fuel source. It was discovered that a boiler orientation such as this one did not present enough surface area to the flame. Therefore, as the water began to flow into the boiler, it cooled and eventually became flooded.

Aside from a boiler orientation problem, the original design experienced problems with leaking. Also, when the reservoir was full, the entire system would become top heavy and unstable. Finally, there was a problem finding a reservoir that would thread mate with the ball valve for an acceptable price. Ultimately this design failed because of the summation of all those reasons. Despite the fact that the design was cost effective, it would have to be heavily modified so that it could operate at steady state for at least one hour.

**Second Design**

There are two standout changes that created the second design. These two changes were a properly mounted reservoir and a horizontally oriented boiler. Also, the system was properly sealed at this stage. For all joints that were not exposed to heat, their threads were wrapped in Teflon® tape. In the case of the boiler and all other joints that were inside the stove, their threads were covered in Oatey's Great White® Pipe Joint Compound which can withstand temperatures in excess of 1200° F. This design can be seen as Figure 4.

The new reservoir allowed the device to have a higher maximum system pressure which resulted in a higher possible exit velocity. Also, the system became less top heavy and unstable because the reservoir was mounted closer to the stove and was sized so it only contained the amount of water that the system would ideally use in an hour. The horizontally oriented boiler resulted in a longer operational period.

This second system, while improved, did not meet the project goals. The boiler was again the main source of concern. Despite the fact that the new boiler orientation would result in functional operation for an average period of 25-30 minutes this was still 30-35 minutes short, and it was believed that a design that would function as long as there was water in the reservoir was a real possibility.

**Third Design**

It was at this stage that the way the reservoir and the flow rate were controlled was changed. A smaller, 1/8" needle valve was introduced at this point. The original design utilized a ½" ball valve, but it was hard to control flow rate at low levels with this valve. The same can be said for the gate valve that replaced the ball valve and the ¼" needle valve which later replaced the gate valve. This whole approach was undertaken because it was felt that the often erratic flow rates from the larger valves had something to do with the fact that the system was constantly flooding, and that it was not just insufficient boiler surface area that was the culprit.

While the smaller, more controllable valve proved to be more efficient at managing the system flow rate, it was not an end-all solution. The system still experienced problems with flooding. It was determined that a whole new boiler design would have to be created, which leads to the final design.

**Final Design**

The completed assembly of the final design is shown in Figure 5. A continuation of testing and design yielded better and more complete results from before. A mockup of a stove unit was provided with similar dimensions and characteristics to the actual cylinders used in the field. The stove unit acquired was made of thin steel, approximately two inch corrugated along the bottom edge and 12 inches tall. The inside diameter was roughly 5 inches and two, one inch holes were punched out at the bottom. One of these holes was used to fit the steam injector apparatus into the interior of the stove.

Multiple designs were implemented and tested throughout the final design phases but the original "hot plate" idea was used. The objective was to eject vaporized water at high velocity and high pressure out of a hole to mix gases in the stove for better efficiency and combustion. An external reservoir full of water placed three feet above the stove created a pressure difference to force water down 1/8" inside diameter flexible plastic tubing. The water's flow rate was regulated by a 1/8" needle valve open to a predetermined angle. From the needle valve, the water travels into gas iron pipe fittings to a $90^{0}$ elbow. The elbow connects to a nipple and another elbow to form a "U" shape. A two inch gas pipe with cap was used for the interior stove reservoir with a 0.05" diameter hole drilled in the top. This final boiler is shown in Figure 6. Washers were used along the nipple to clamp the apparatus to the stove and keep it from rotating. The flame used in this experiment was of natural gas to ensure a consistent and reliable heat source readily available for testing. The heat from the flame increased the temperature of the iron fittings to ensure an instant boil. The effect was similar to water spilled on an iron's hot surface, the water instantly vaporizes and rises into the reservoir. When the pressure inside the reservoir is too great, the steam is ejected into the stove through a small diameter hole drilled in it. Overall the concept is self contained and only uses power from the flame's heat to run the system; no electrical timers, switches, relays, or human intervention is needed.

**Cost Analysis**

Many of the pieces used in the steam injector for the biomass stove were bought at the local hardware store and are therefore wholesale prices. The iron fittings including the elbows, 2" pipe and caps, and couplers and nipples cannot be eliminated because they are unique and essential to the design; however, multiple reducers were used to fit the needle valve to the ½" pipe and fittings along with the larger diameter caps. Upon further analysis, these fittings could be reduced to a single reducer through a plumbing specialty store. Although the price of the final design does not exceed $31.00 in materials alone, cost will be reduced further by eliminating redundant parts. The cost of the final product design is outlined in Table 1.

The labor for assembly of the final stove design is quite simple with an estimated time of assembly of three and a half minutes. The hole drilled into the reservoir for the steam injection consumes the only specialty machining but only takes one minute. Overall, the assembly will take approximately four minutes and thirty seconds to machine and construct. The parts list will far outweigh the build time cost.

An in depth yet conservative estimate for total cost must take into account large volume production including bulk material pricing. The pipe dope and thread tape were only used sparingly on the apparatus and under mass quantities, could be used for multiple steam injector stove assemblies. The reduction in the cost for pipe dope will significantly affect the final price. Gas fittings are also sold in bulk at plumbing supply stores and could be reduced if many stove units were compiled. Overall, the reduction in materials cost would offset the cost of labor for assembly and machining of the steam injectors and could possibly reduce the total unit price to under $30.00. With portable grills located throughout the hardware stores and priced under $20.00, the steam injector may seem uneconomical but, without the means of refilling the propane or providing mixing of gases, these grills will not suffice for the interior of homes in developing countries.

**Quantitative Analysis**

The majority of the work on the project was dedicated to getting a consistently functional system. Once this was achieved the work became more focused on both making sense of what was happening and analyzing the system to learn of potential benefits or drawbacks. The first experiment that was run was on the needle valve independent of the rest of the system. The test consisted of altering the valve opening while keeping the water column height constant. This test was run at three different water column heights. The results can be seen in Figure 7 and were about what was expected. One thing that can be concluded from this test is that as long as the water reservoir is somewhere between two and three feet above the needle valve, a consistent flow rate should be seen.

After a consistent flow rate was observed, a maximum flow rate needed to be determined. These MATLAB calculations can be seen in Figure 8. The assumptions made to make these calculations meaningful are as follows:

- Discharge coefficient of .6

- Constant water column height of 1 meter
- Instantaneous and constant boiling, i.e. conservation of mass in the boiler
- Boiler pressure equal to or less than column height water pressure (to keep from having steam boil up through the feed line)

These assumptions and calculations produced a steam exit velocity of 180 m/sec. Using this exit velocity a maximum flow rate of .09 mL/sec was determined.

To verify the theoretical calculations, a test of the flow rate of the system completely assembled was done. The test was done by increasing the valve opening until bubbling through the water feed line was observed. Once this happened the valve position was noted and then the valve was closed, any excess water in the system was allowed to boil off. Once there was no steam heard ejecting from the system, the valve was opened to the noted position. The system was then allowed to run for 30 minutes. The time was noted for every ten mL of water consumed. The results of this test, as well as a best fit curve, can be seen in Figure 9. The slope of the line is the flow rate of our assembled and working system in mL/sec and is noted as .0888 on the figure. The results of this test back up what we had expected from our theoretical calculations.

## Conclusion

As the steps of the steam injector design process were completed, a successful system was created. The system designed was very simple, cost effective, had no need for electricity, provided for infrequent refilling of water, eliminated the risk of dumping liquid water onto the fire, was non-clogging, could not over-pressurize or explode, and consumed a small amount of energy. These features provided for all of the initial design requirements to be met.  Also, the system's ability to run and control itself safely for an extended period of time were extra features the design allowed.

In the future, more extensive testing on the design could be performed.  The energy consumed by the design could be compared with the energy consumed by the existing design.  This comparison would likely prove the design to be a more efficient means of steam production.  Also, a test showing the effectiveness of the working system on actual pollution reduction would be helpful.  The design requirements called for steam production, but numbers showing actual pollutant amounts with and without steam injection would show the usefulness of the system created.  Overall, the design provides a very good start attacking the problem of pollutant production in biomass burning stoves.

## REFERENCES

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## ACKNOWLEDGMENT

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**Figure 1: Existing Chinese Steam Injector**

**Figure 2: Initial Prototype**

**Figure 3: Initial Prototype Boiler**

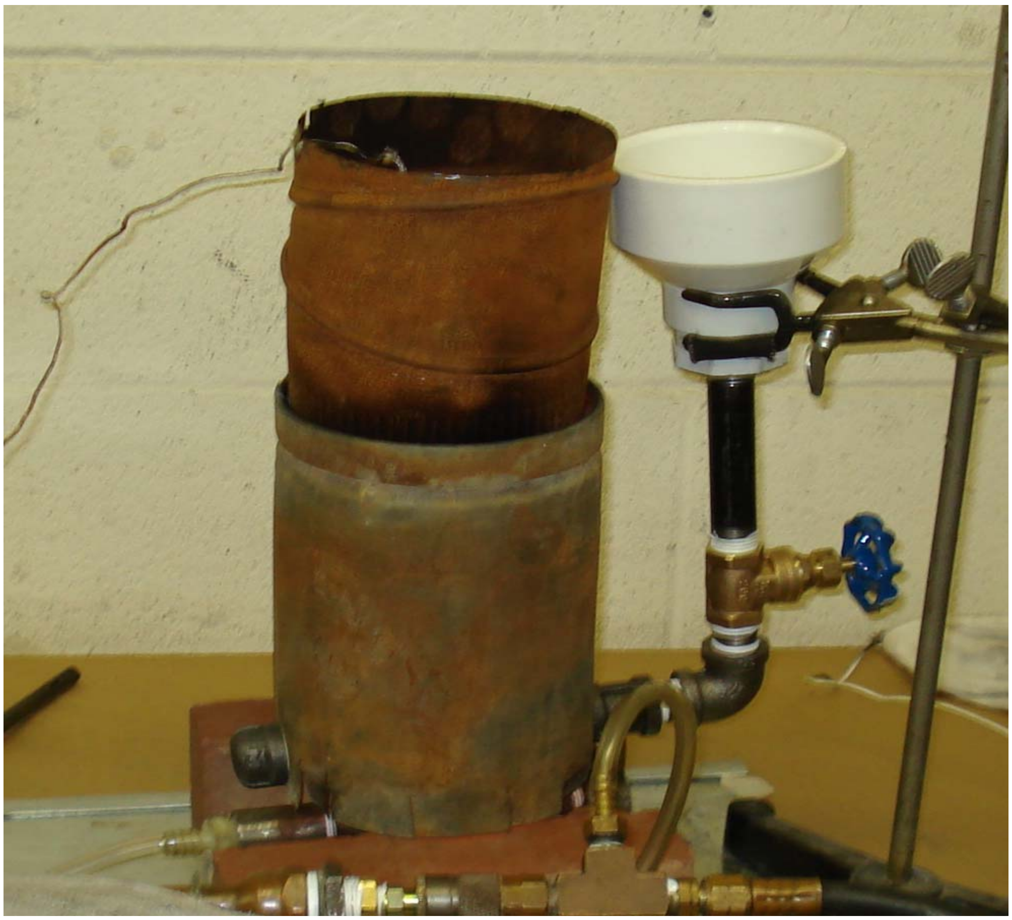


**Figure 4: Second Design**

**Figure 5: Completed Final Design**

**Figure 6: Final Boiler Design**

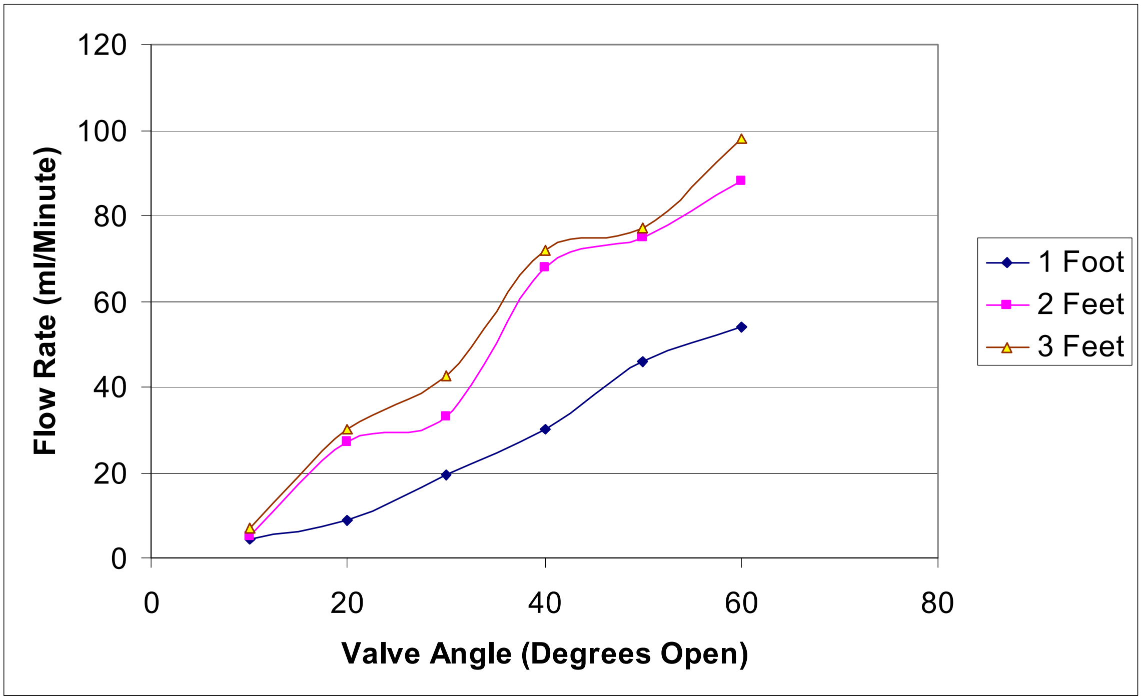
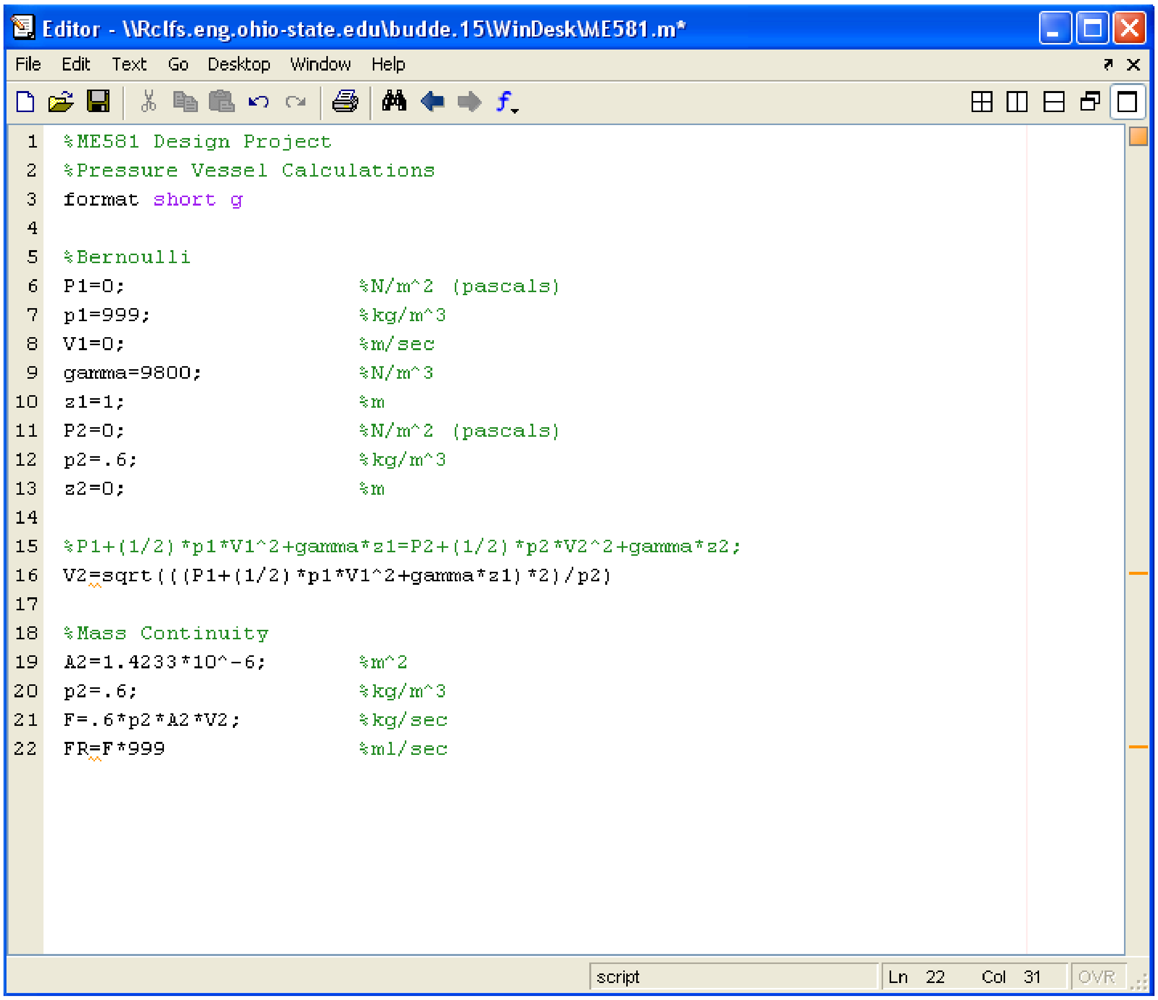



**Figure 7: Experimental Needle Valve Flow Rate**



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%Pressure Vessel Calculations
format short g

%Bernoulli
P1=0;                   %N/m^2 (pascals)
p1=999;                 %kg/m^3
V1=0;                   %m/sec
gamma=9800;             %N/m^3
z1=1;                   %m
P2=0;                   %N/m^2 (pascals)
p2=.6;                  %kg/m^3
z2=0;                   %m

%P1+(1/2)*p1*V1^2+gamma*z1=P2+(1/2)*p2*V2^2+gamma*z2;
V2=sqrt(((P1+(1/2)*p1*V1^2+gamma*z1)*2)/p2)

%Mass Continuity
A2=1.4233*10^-6;        %m^2
p2=.6;                  %kg/m^3
F=.6*p2*A2*V2;          %kg/sec
FR=F*999                %ml/sec
```

**Figure 8: Theoretical MATLAB Flow Rate Calculations**

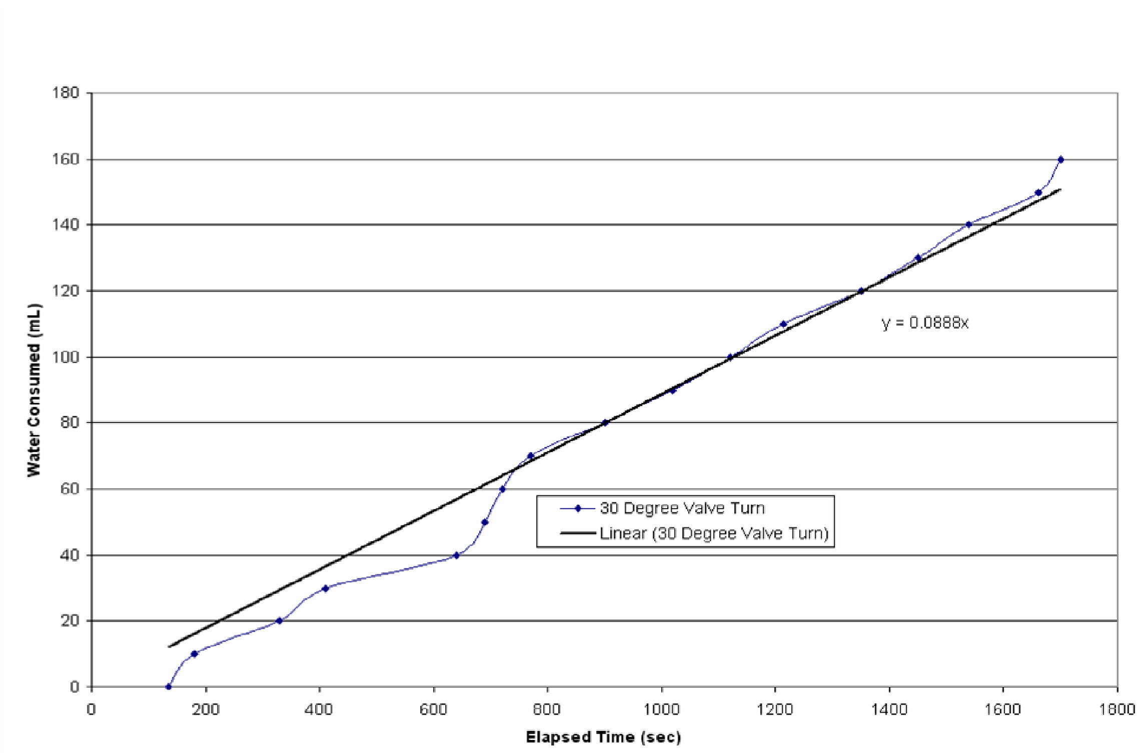


**Figure 9: Experimental Working Assembly Flow Rate**

**Table 1: Cost of Final Product Design**

| | | | |
|---|---|---|---|
| Item | Individual Price | Quantity | Total Price |
| 4 Oz Can Pipe Dope | $3.47 | 1 | $3.47 |
| Joint Threaded Sealant Tape | $0.97 | 1 | $0.97 |
| 2" Threaded Black Iron Cap | $2.97 | 1 | $2.97 |
| 2" Threaded Coupler | $1.84 | 1 | $1.84 |
| 1/2" Threaded 90˚ Reg. Elbow | $0.87 | 2 | $1.74 |
| 1/2" Threaded Galvanized Coupling | $1.27 | 1 | $1.27 |
| 1/2" x 1" Black Iron Pipe Reducer | $1.53 | 1 | $1.53 |
| 1/2" x 1/8" Reducer | $0.88 | 1 | $0.88 |
| 2" to 1" Black Iron Pipe Reducer | $3.88 | 1 | $3.88 |
| 1/2" Black Iron Pipe Nipple | $0.86 | 3 | $2.58 |
| 2" Washer | $0.39 | 4 | $1.56 |
| 1/8" Barb | $2.06 | 1 | $2.06 |
| 1' of 1/8" Plastic Tubing | $0.08 | 5 | $0.40 |
| 1/8" Needle Valve | $4.26 | 1 | $4.26 |
| Plastic Water Bottle | $1.00 | 1 | $1.00 |
| | Grand Total | | $30.41 |