9-13-2009

Sustainable Design Analysis of Waterjet Cutting Through Exergy/Energy and Lca Analysis

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Sustainable Design Analysis of Waterjet Cutting Through Exergy/Energy and Lca Analysis

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering
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Date of Approval:
September 13, 2009

Keywords: biological systems, environmental impact, sustainability, exergy analysis, green engineering

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ABSTRACT

A broad scope analysis of waterjet cutting systems has been developed using thermodynamics, life cycle analysis, and biological system comparison. The typical assessments associated with mechanical design include measures for performance and thermodynamic efficiency. Further analysis has been conducted using exergy, which is not typically incorporated into design practices.

Exergy measures the effectiveness of a process with respect to a base state, usually that of the systems surroundings. Comparing Gibbs free energy of biological processes to exergy efficiency has served to illustrate the need for various levels of comparison. Each biological process used in this comparison correlates to a different type of mechanical process and level of complexity. Overall, biological processes display similar properties to mechanical systems in that simpler systems are more energy efficient.

In order to determine accurate efficiency and effectiveness values for a mechanical process, in this case waterjet cutting, a set of thermodynamic models was

established to account for energy uses. Various output force and velocity models have been developed and are used here for comparison to assess output efficiencies with "no loss" models used as a lossless base. Experimental testing was then conducted using a simple nozzle and a pressure washer with 2 other diameter nozzles. The most energy efficient system used a turbojet nozzle. It was also the most efficient sustained system with energy inputs. However, it had a much lower exergy efficiency compared to the other systems. This implies that it could be significantly improved by more adequately utilizing the energy provided.

An effort to assess the green nature of pressurized water systems was done through use of an Economic Input/Output Life Cycle Analysis (EIO-LCA). The EIO-LCA is designed to assess processes for greenhouse gas emissions and total power consumption across the life of a system. Calculations showed that increases in power consumption result in much higher greenhouse gas emissions per unit time than increases in water consumption. Financial cost however showed an opposite trend due to the much greater cost of water with regard to consumption rates in each system. The most "green" system used only a nozzle with no power consumption.

Chapter 1: Introduction

Waterjet cutting is considered a highly efficient manufacturing method. The process involves the use of highly pressurized water as a cutting medium which imparts negligible amounts of heat to the work piece being cut. As such, the parts created by this form of manufacturing incur no change in crystal structure typically caused by heat generated in other metal removal processes.

The analysis of such a manufacturing process from an exergy standpoint may serve as a preliminary indicator as to how effective it is. Existing models of this process will be extended to determine both the thermodynamic efficiency and effectiveness of a waterjet machining process. The model will then be assessed for accuracy through experimental trials and then for evaluating its usefulness in identifying key parameters that affect the efficiencies and effectiveness.

Manufacturing process comparison to cellular processes may also be useful in determining sustainable design metrics. Cellular processes are typically assessed on a Gibbs free energy basis, which is similar in methodology to an exergy analysis. As some biological systems are highly efficient in the use of available resources while minimizing waste, a comparative analogy between a waterjet and variable scale cellular systems could prove invaluable in determining a set of sustainable design metrics for mechanical systems which may result in higher efficiencies, effectiveness and better resource utilization while minimizing ecological impact and waste. Similarly, a life cycle analysis of waterjet cutting should also identify which aspects of the process have the most impact on those economical and ecological facets.

Chapter 2: Background

While the focus of this analysis is rooted in mechanical engineering, there are many cross-disciplinary terms and ideas which will be introduced. This background is meant to act as a primer for introducing the knowledge required to relate the ideas being presented.

2.1. Waterjet Cutters

The advent of what may be considered modern waterjet cutting brought with it what can only be described as an amalgam of manufacturing possibilities. Modern waterjets use pressures in the range of 200 – 800 MPa with exit velocities which may approach 1200 m/s.[1-10] Water at that velocity acts in much the same way as a saw, cutting through very hard materials. Cutters are usually attached to a number of servos which allow for computer numberically controlled (CNC) machining.[1] The most influential aspect of using a waterjet cutter over standard machining alternatives, is that the water stream does not heat the material during cutting.[1] This prevents the typical heat affected zones and possible sub-surface damage which may be present after traditional cutting. As such, material properties can be held at nominal values and are as such, much more likely to act as designed.

2.1.1. Crack Propagation Model

For waterjet cutting, material removal occurs by crack propagation.[1,2,5,7,9] Materials science dictates that in order for cracking to occur, a defect or dislocation in an affected material must be present. In other words, materials which have failed from the extenuation of a crack already had a defect present, such as in the form of a microstructural anomoly. Waterjets serve to promote crack growth by imparting localized pressure fields on a surface, exploiting the nature of these defects and eventually cutting completely through the material.[1] Typically, more brittle materials fail under this mechanism.[1]

2.1.2. Abrasive Waterjet

An abrasive waterjet acts similarly to a standard waterjet in that the force imparted comes from a combination of stream velocity and pressure. Abrasive waterjets differ in that abrasive additives are mixed into the water stream, typically an abrasive garnet in the range of 80 grit.[1-10] The addition of hardened particles acts to increase stream cohesion and impart higher levels of kinetic energy.[1-10] The addition of garnet for instance, will allow a water stream to cut through very hard and brittle materials such as titanium with very low resource utilization. It has also been suggested that the addition of abrasive particles may serve to decrease the cost per unit length when cutting materials through reduction in the water and electricity required to cut a medium.[2] A detailed diagram of a standard abrasive waterjet cutting head assembly is present in Figure 1.

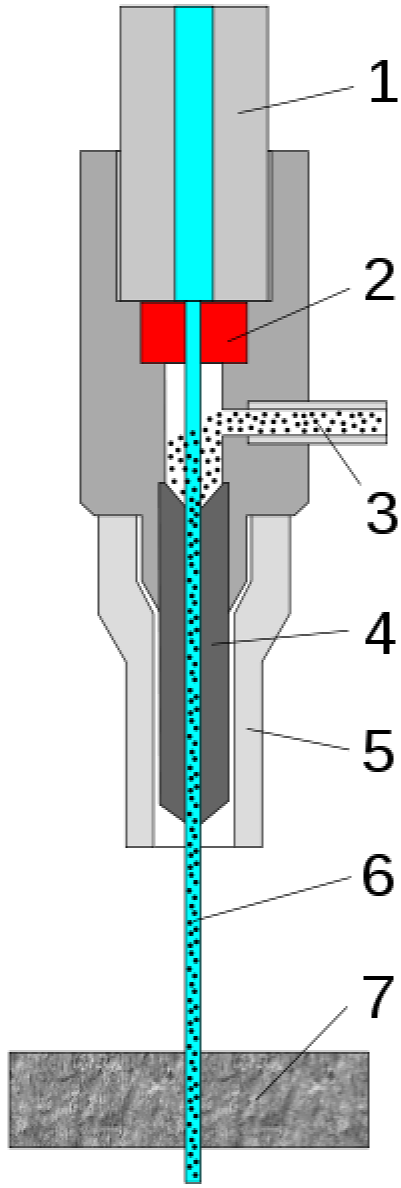

Figure 1: Waterjet Cutter Head; 1 - high-pressure water inlet, 2 - jewel (ruby or diamond), 3 - abrasive (garnet), 4 - mixing tube, 5 - guard, 6 - cutting water jet, 7 - cut material. Source: Zureks, Waterjet Cutter Head, http://commons.wikimedia.org/wiki/File:Water_jet_cutter_head.svg

2.1.3. Impingement Failure Model

The impingement model for material removal details plastic deformation as the cause of primary failure.[1] Ductile materials such as metals typically undergo this type of failure during waterjet cutting.[1,5,9] Evidence of this has been shown in a variety of papers whereby an abrasive waterjet embeds partiles of abrasive in the metal. This acts to cause localized areas of highly strain hardened material. The material, in essence, surrounds the embedded particle in a sheath. The bombardment continues this trend until the material has completely flown out of the path of stream travel or until the stream and abrasives have broken through following impact due to cracking.[1,5,9] Because of the likelihood of embedding particulates rather than removing material, a non perpendicular angle of attack is sometimes used, whereby knicks in the cut zone are created due to glancing impacts.[1]

2.2. Design Methodology

Common practice for design of modern technology is performance based.[11-18] In essence, this means that the goal of design is to achieve a particular performance level with product efficiency. In this respect, other design considerations such as resource utilization or environmental impact are often times only taken into account when deemed an economical shortcoming.

2.2.1. Efficiency

Efficiency is typically assessed on an output vs. input basis.[11] In other words, effeciency for a pump is merely a performance measurement which defines the ratio of output to input as defined by Equation 2-1. The first law of thermodynamics then dictates that output can never exceed input, and as such, the ratio must always fall between 0 and 1. For a value of 1, all energy input would be exchanged as output whereas for a value of 0, all energy input would be lost. The amount of energy lost can be the result of friction, heat transfer to the surroundings, or improperly designed components. These losses all act to limit the highest efficiency a proccess can achieve, according to a first law analysis.[11]

$$\eta = \frac{Output}{Input} \qquad \textbf{(2-1)}$$

2.2.2. Effectiveness

Effectiveness, or Exergy efficiency, uses the standard formula for efficiency but also takes into account exergy destruction. Effectiveness assesses the quality of energy used with regard to the maximum obtainable work in a system.[11] In essence, the system is being compared to an ideal Carnot engine's use of energy. This means that the energy used is being compared to the maximum potential of heat energy being used in the form of work.[17] Equation 2-2 defines exergy destruction, or irreversibilities as surrounding temperature multiplied by the change in entropy from entry to exit.[11,17]

$$I = T_o * (s_1 - s_2) \qquad \textbf{(2-2)}$$

2.2.3. Sustainable Design

The idea of sustainable design is not a new one. One recognized application of such a design methodology is intended to minimize negative environmental impact with regard to the *12 Principles of Green Engineering*. [18] The 12 principles are listed as follows:

1. Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible.

2. It is better to prevent waste than to treat or clean up waste after it is formed.

3. Seperation and purification operations should be designed to minimize energy consumption and materials use.

4. Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.

5. Products, processes, and systems should be 'output pulled' rather than 'input pushed' through the use of energy and materials.

6. Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.

7. Targeted durability, not immortality, should be a design goal.

8. Design for unnecessary capacity or capability (e.g., 'one size fits all') solutions should be considered a design flaw.

9. Material diversity in multicomponent products should be minimized to promote disassembly and value retention.

10. Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.

11. Products, processes, and systems should be designed for performance in a commercial 'afterlife.'

12. Material and energy inputs should be renewable rather than depleting.

2.2.3.1. Life Cycle Analysis

The intent of a life cycle analysis is to determine not only economic impact but also environmental impact over the life of a process.[15] Economic impacts cover the financial costs assessed either per unit time for usage or for the total life if known. Some of the relevant variables include cost of the object, power usage, chemical usage, and any relevant maintence costs. Environmental impacts cover the creation of any environmental hazards as a result of the process. These may include but are not limited to greenhouse gasses or wastes.[15]

2.3. Biological Systems

2.3.1. Organelle

At the most basic level, an organelle may be considered as one of the many specialized components that make up a typical eukaryotic cell. Each eukaryotic cell, also known as an animal cell, has a standardized make up. This does not change with differentiation of cell types. In other words, a muscle cell will have the same organelles as an epithelial cell, albeit in possibly different concentrations.[19] Table 1 lists a number of these organelles and their functions within a cell.[19]

Table 1: Common Organelles and Associated Functions

Organelle	Function[19]
Golgi Apparatus	Process all incoming proteins, enzymes, and lipids while at the same time also controlling their export.
Lysosomes	Break down particles, other cells, and old organelles for reutilization of resources.
Nucleus	Acts as the brain of the cell, serving to moderate and control internal resources as well as external actions.
Mitochondrion	Serve to create ATP as a fuel to power cellular functions.
Ribosomes	Convert nucleic acids into proteins using mRNA as a template.

2.3.2. Cell

The cell is the smallest living biological entity. Cells are the basic building blocks for any more complex organism.[19] While cells vary in function and size, each has a number of the same basic organelles.[19] Figure 2 details the general makeup of a eukaryotic (animal) cell with some of these common organelles identified.

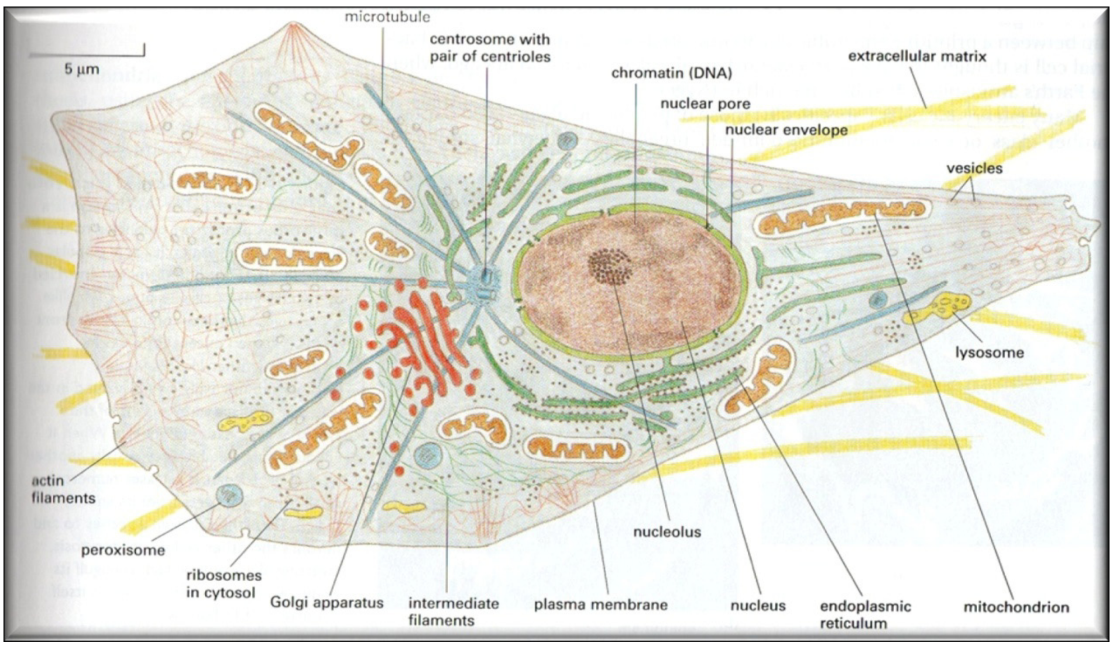

Figure 2: Animal Cell[19]

2.3.3. Organ

Biology defines an organ as a component or system which is made up of a collection of tissues and cells with a common purpose.[19] Organs typically have a primary tissue type which is specific to the organ as well as secondary general tissue types which are common to most organ types. Organs are similar to organelles in that they operate to serve a larger system such as an organism.

2.3.4. Gibbs Free Energy

Gibbs free energy is a term used in the biochemistry field to define the second law of thermodynamics.[19] In this respect, it is similar to exergy in that they both measure how much energy a system can utilize if the conversion energy was directly from heat to work. Gibbs free energy is assessed with regard to the system temperature and the change in enthalpies and entropies from state 1 to 2.[19] Rather than measure the actual amount of energy available, it merely measures the change in energy availability or ΔG.[19] The standard Gibbs free energy equation is defined in Equation 2-3. A more applicable definition for the purposes of comparison is defined in Equation 2-4.

$$\Delta G = \Delta H - T\Delta S \qquad \textbf{(2-3)}$$

$$G_1 - G_2 = (H_1 - H_2) - T * (S_1 - S_2) \qquad \textbf{(2-4)}$$

Chapter 3: Thermodynamic Model

A variety of analyses have been conducted on waterjet cutters which encompass its performance aspects. An analysis which assesses both 1st and 2nd law efficiencies has not been done however. As such the implementation of such an analysis requires the use of model designed to assess the energy usage with regard to performance. Most models for waterjet cutting ignore the energy requirements associated with increased water pressurization and as so, they are not entirely relevant to determining efficiency or effectiveness.

A typical method for assessing energy output and requirements for a water stream is to analyze the changes in enthalpy, kinetic energy, and potential energy. Equation 1 identifies the basic equation for assessing these terms. The $\dot{m}$ term is mass flow rate in kg/s and indicates that the stream will be measured with respect to time. Figure 3 displays an ideal system for use with this model and the required measurements.

$$\dot{W}_{1s} = \dot{m}(h_1 - h_{2s}) + \dot{m}\left(\frac{Vel_1^2 - Vel_2^2}{2}\right) + \dot{m}\left(g * (z_1 - z_2)\right) \qquad \textbf{(3-1)}$$

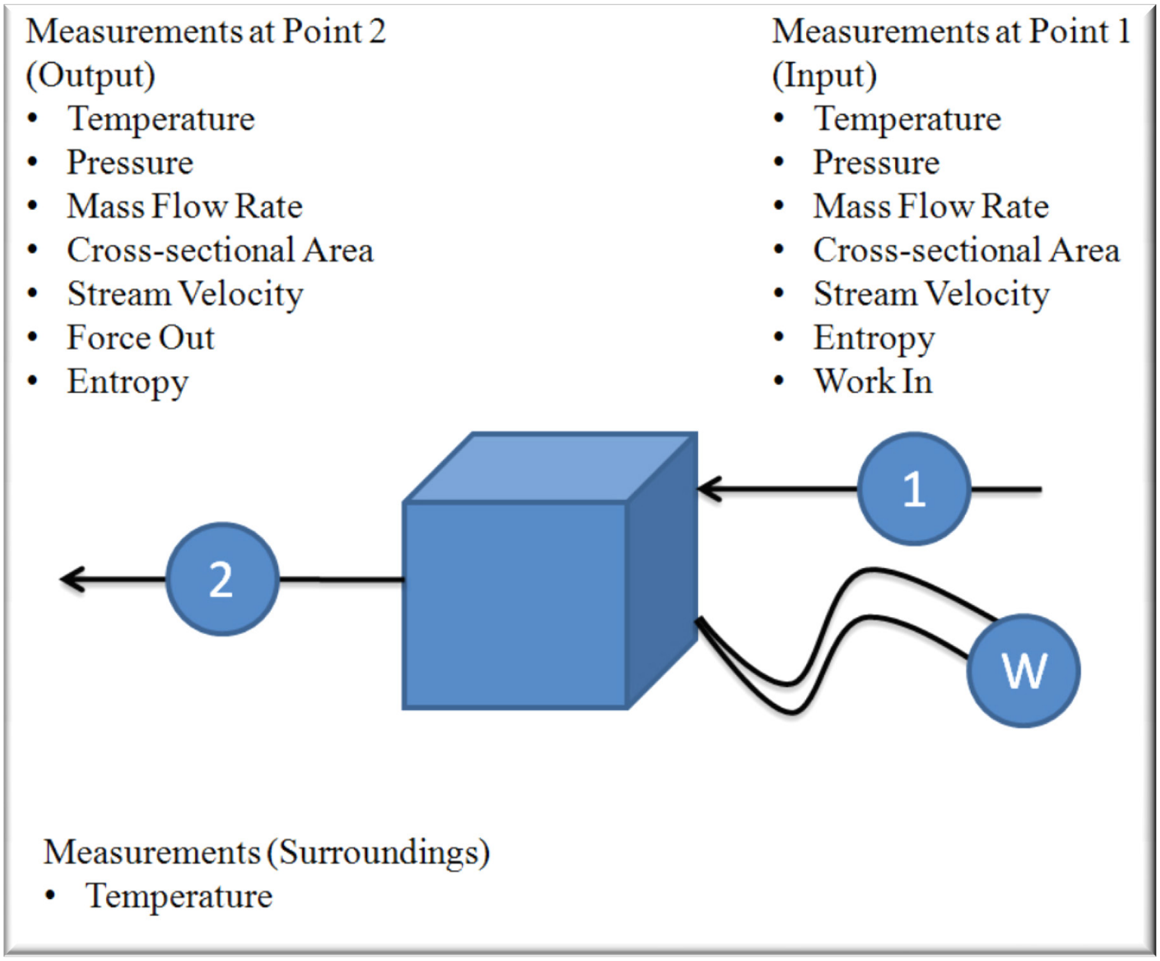

Figure 3: Model System & Measurements

W_{is} refers to the isentropic or "no loss" work associated with a stream and is measured in J/s or Watts. The h_1 and h_{2s} terms refer to the specific enthalpy associated with the stream at entry (point 1) and exit (point 2). Typically, specific enthalpy is assessed on a J/kg basis and can be measured by temperature and pressure relationships associated with a fluid. In a typical waterjet system however, there is a minimal increase in temperature whereas pressure may increase drastically.

To more accurately assess such a relationship, an equation for determining specific enthalpy from internal energy, pressure, and specific volume will be used.

$$h = u + P\nu \quad \textbf{(3-2)}$$

Specific volume is denoted by υ and is assessed on a m^3/kg basis. P denotes pressure in Pascals, and u represents internal energy in J/kg. By replacing specific enthalpy with Equation 3-2 in Equation 3-1, a difference in pressures with respect to specific volume can be found. Internal energy should most likely remain constant so long as water is considered incompressible. This demonstrates that an increase enthalpy will result not from temperature increase, but from pressure increase.

Vel is used to denote velocity and when paired with mass flow rate, closely resembles Equation 3-3, which defines the kinetic energy of an object. This again means that the 2nd set of terms in Equation 3-1 is actually a measure for the difference of kinetic energy from the entry to exit. When used at just the exit however, Equation 3-3 may be used to assess the maximum possible impact force from a water stream at exit velocity. It may also be used with the cross sectional area A of the stream to find the pressure of the water stream on the impact surface. Force is measured in J/s.

$$\dot{F} = \frac{PA}{t} = \frac{1}{2}\dot{m} * Vel^2 \quad \textbf{(3-3)}$$

At this point however, another issue arises. There will be a difference between the actual impact force and calculated impact force. This occurs due to a variety of issues, including that a water stream does not act as a solid object would. A number of factors affect how closely a stream of water will act compared to a solid object. Chief among these are Reynolds Number, which defines how laminar or turbulent a stream is, and stream pressure, which acts to increase transmissivity. Equation 3-4 defines the Reynolds number, Re, at a nozzle exit with diameter D and kinematic viscosity υ.

$$Re = \frac{Vel*D}{\upsilon} \quad \textbf{(3-4)}$$

Finding entry and exit velocities may be easier through base calculation involving water density, cross sectional area, and a measured volumetric or mass flow rate. For this purpose three relationships have been established. The first (Equation 3-5) relates volumetric flow rate to mass flow rate using water density. The second equation (Equation 3-6) relates mass flow rate to velocity and cross sectional area using density. The third and final relationship (Equation 3-7) may be used to find the relation between entry and exit velocities by assuming that mass flow rate in is equivalent to mass flow rate out and that density remains constant.

$$\dot{m} = \dot{V} * \rho \quad \textbf{(3-5)}$$

$$\dot{m} = \rho * Vel * A \quad \textbf{(3-6)}$$

$$Vel_1 * A_1 = Vel_2 * A_2 \quad \textbf{(3-7)}$$

The last of the three terms found in equation 3-1 refers to the difference in potential energy. Fortunately, in most systems, the potential energy difference is in fact not substantial. This is because, unlike the velocity terms, the heights are not squared. This means, at a height difference of even 1 m, the energy lost in a typical waterjet system using roughly 0.1 kg/s mass flow rate would equate to just 0.98 Watts compared to the energy input of a standard waterjet cutter being somewhere near 23 kWatts.

At this juncture, each of the terms in Equation 3-1 may be assessed using nominal values based on constant inputs measured such as mass flow rate, pressure in, and geometry of both the entry and exit ports. From Equation 3-7, velocity out may be found and input to Equation 3-3. This will yield a lossless force value and associated output pressure. Using the pressure and force values in Equation 3-1 should then yield an isentropic work value. This is essentially a minimal work required value which signifies the lowest possible amount of energy which could be input to create the equivalent pressure and output force.

Due to losses inherent to any system, this value of isentropic work will never be achieved. With that in mind, an efficiency value can be found through the use of Equation 3-8. Division of isentropic work values by actual work input will yield an efficiency rating.

$$\eta = \frac{\dot{W}_{is}}{\dot{W}_a} \qquad \textbf{(3-8)}$$

The overall effectiveness or exergy efficiency of the system may then be determined through the addition of a term governing exergy destruction. The exergy destruction is based on the surrounding temperature and the differential between entry and exit specific entropy values. This term is designed to account for the amount of energy which can never be recovered from the exchange of energy occurring within the boundaries of the system. Equation 3-9 shows the basic exergy equation. Equation 3-10 then shows effectiveness utilizing a comparison between exergy and actual work input.

$$\Phi = \dot{m}(h_1 - h_{2a}) + \dot{m}\left(\frac{Vel_1^2 - Vel_{2a}^2}{2}\right) + \dot{m}\big(g * (z_1 - z_2)\big) - \dot{m}\big(T_0 * (s_1 - s_2)\big)$$

(3-9)

$$\varepsilon = \frac{\Phi}{\dot{W_a}}$$ **(3-10)**

When effectiveness approaches the value calculated as efficiency, it means that low amounts of energy are lost in energy conversion. It is important to note that efficiency compares losses in energy relevant to a system whereas effectiveness compares a system's energy utilization in so much as various types of energy use carry with them a higher transmissivity and innate ability to maintain higher levels of order. For this waterjet cutter model, this suggests that the force comes mostly from the achievement of higher levels of velocity. Velocity increase is therefore obtained through a combination of minimizing nozzle geometry with respect to entry geometry and an increase of mass flow rate through use of pressurization.

Chapter 4: Experimental Assessment of Thermodynamic Model

To test the validity of the model, an experimental apparatus has been constructed with sensors designed to monitor the needed thermodynamic components of the system. Among these components are volumetric flow rate, ingoing and outgoing temperature, ingoing pressure, and outgoing force. These components may then be used with the model to assess efficiencies of the various test systems.

The first test system analyzed is that of a simple pressure driven nozzle. Essentially, the force to be imparted comes from the change in cross-sectional area from the supply hose to the nozzle. The nozzle is roughly 1/30th the size of the supply hose, which in turn amplifies the input velocity by 30 times at the output. The nozzle cross-sectional area is about 6.7E-06 m^2. It is important to note the water flow is driven solely by standard plumbing water pressure which was measured to be 80 psi.

The second and third systems analyzed utilize a pressure washer rated for 1800 psi output. The difference between systems two and three is the nozzle type used. System two uses a slightly divergent nozzle with a 0.125" diameter while system three uses a 0.175" diameter flat nozzle. The second system has an approximate nozzle cross-section ratio of 1/25th the input hose, whereas the third system has approximately a 1/13th ratio. Based on Equation 3-7, it is logical to assume that a higher input:output ratio will result in higher velocity output, and as such, higher force output. Table 2 designates the nozzle geometry values and input:output ratios.

Table 2: Nozzle Dimensions

	System 1	System 2	System 3
Nozzle Diameter (m)	2.921E-03	3.175E-03	4.445E-03
Nozzle Area (m^2)	6.704E-06	7.920E-06	1.552E-05
Input : Output Area	29.5	25	12.76

Implementation of the model assessment (photos available in Appendix 1: Figure 18) was conducted with respect to the following procedure and was reiterated for each of the three systems being tested:

1. Mount the force load cell on the target grill with the impact plate affixed on top.
2. Mount the nozzle assembly such that the stream impact will be perpendicular to the load cell. Minimal distance between the nozzle and the impact plate should be maintained to minimize velocity losses due to stream dispersion.
3. Once mounted, the load cell is calibrated in order to zero the force readout while the impact plate is affixed.
4. To measure volumetric flow rate, an inline flow meter is utilized and values are recorded on a unit time basis.

5. A watts-up meter is used to measure and record power input values.
6. Before each trial, the force readout is once again zeroed in order to maintain accuracy and to assess the maximum burst output for each trial.
7. Discharge of the water stream should occur until values reach or approximate steady state values. Values to record during this period are flow rate, power input, force output, surrounding temperature, output stream temperature, and input stream temperature.
8. Efficiencies, exergies, and other values are then calculated from the afore mentioned thermodynamic models.

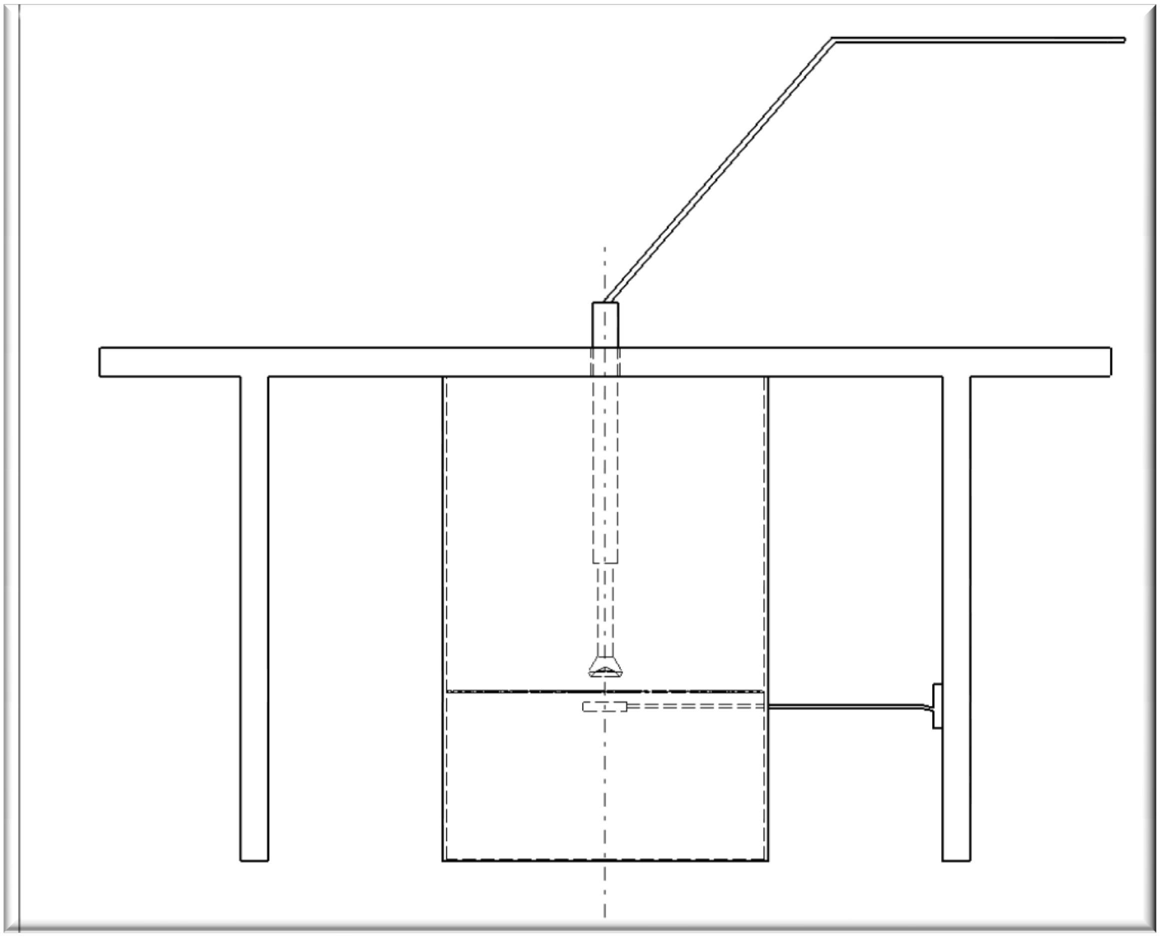

Figure 4: Cross Section of Test Stand

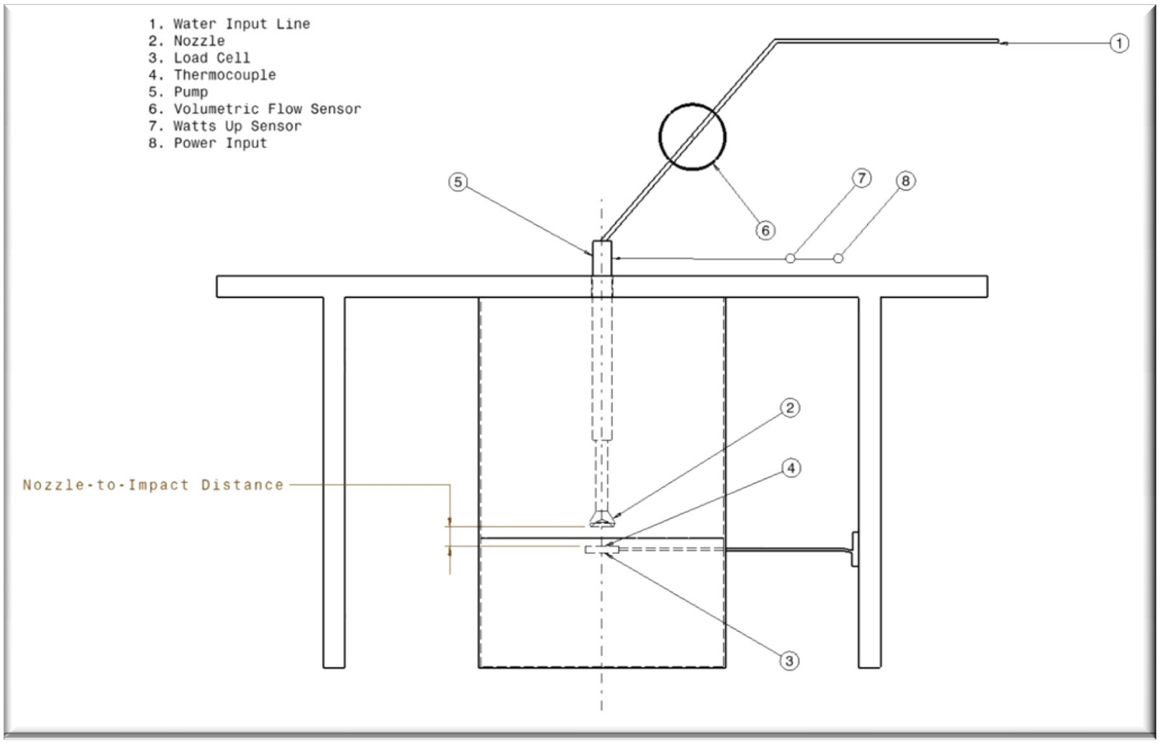

Figure 5: System Diagram With Sensor Placement

The mass flow rates are found by assessing the volumetric flow rate (m^3/s) and converting to mass flow rate (kg/s) through a relationship described by Equation 3-5. The mass flow rate does not necessarily correlate to cross sectional area as denoted by Figure 6. Rather, the flow rate is driven up by increased pressurization.

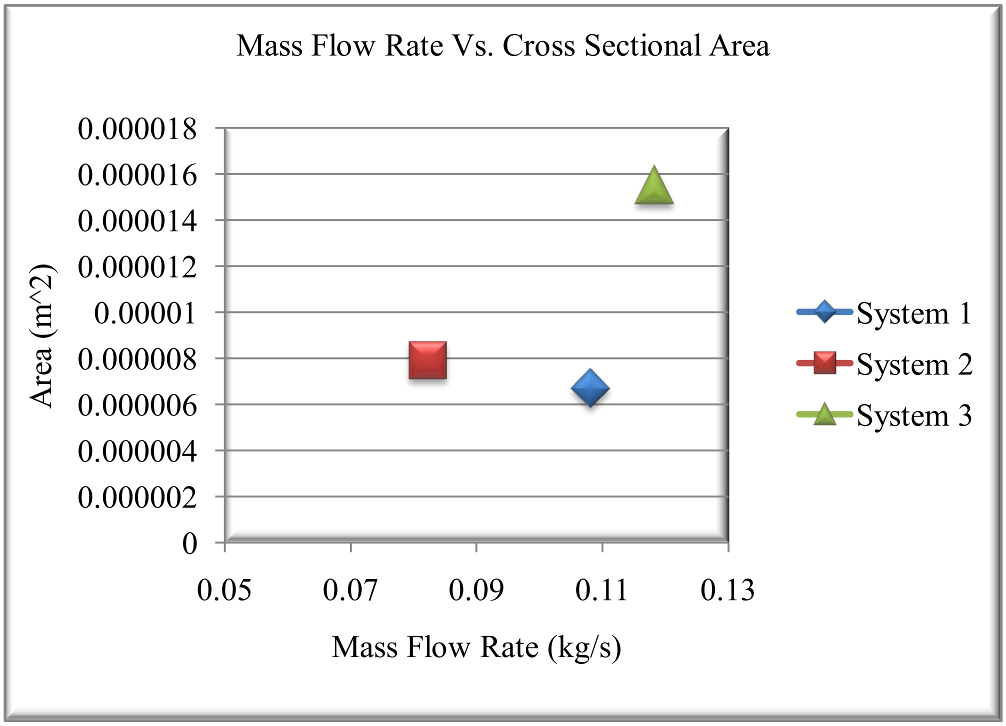

Figure 6: Mass Flow Rate Vs. Cross Sectional Area

Individual volumetric flow rates and by extension mass flow rates were found to be constant across trials with minimal variability. As such, a mean value was used for each system as the basic mass flow rate in the calculation of the other associated variables.

Input velocity values were found using the relationship described by Equation 3-6. These input velocities are directly associated with the geometry of the input hose, mass flow rate, and a specific volume value related to the temperature of water. As water is considered to be an incompressible Newtonian fluid, the value for specific volume was found from thermodynamic tables and used across trials as a constant value. As the mass flow rates between each system varied, input velocities also varied correspondingly. Of the three systems defined, system 2 had by far the lowest input velocity as denoted by Figure 7.

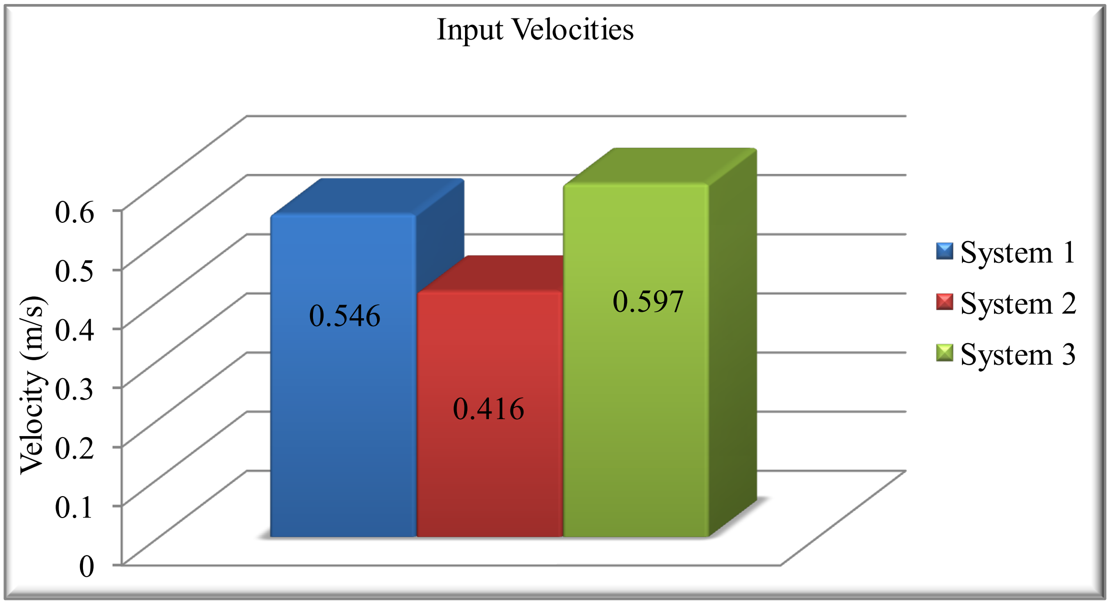

Figure 7: Input Velocities

After calculating input velocities, it is a relatively straightforward process to determine the exit velocity. Output velocity corresponds to input velocity through the flux Equation 3-7. The relation is that of velocity proportional to cross sectional area being equivalent for both entry and exit if mass flow rate is held constant. It is interesting to note that while system 2 had the lowest input velocity, it is in fact not the lowest output velocity. Figure 8 shows the comparison between input and exit velocities with regard to each system.

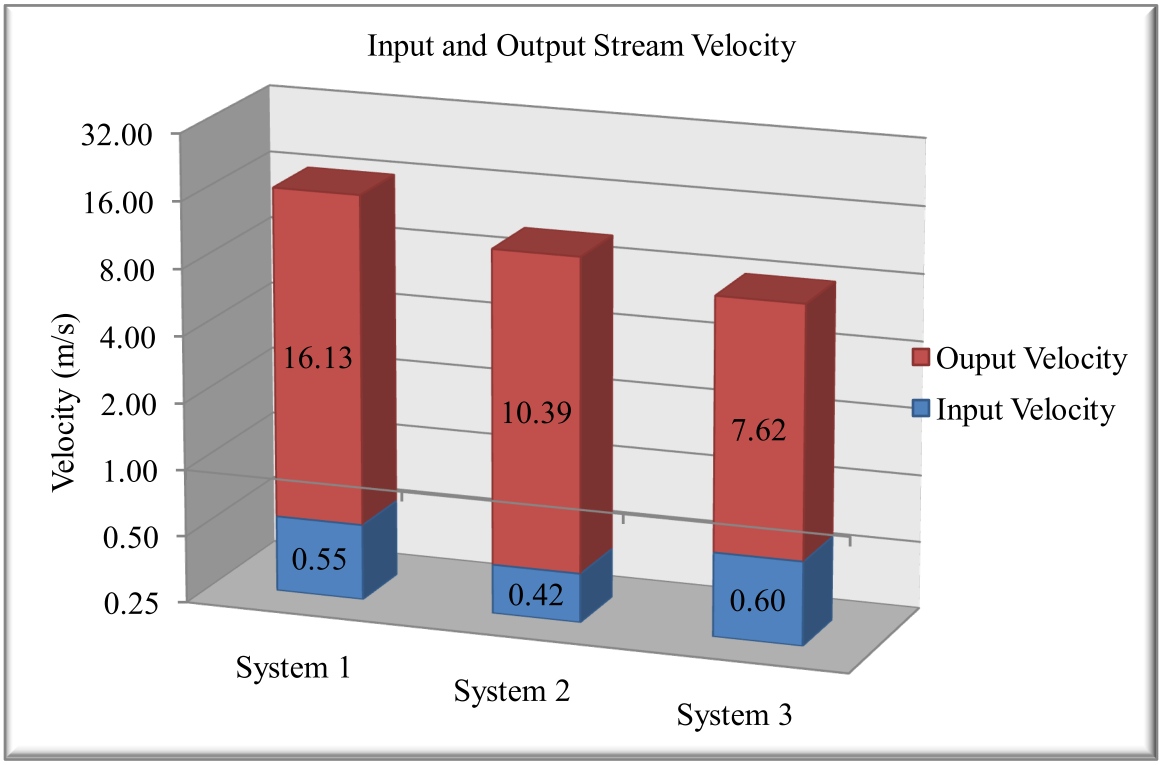

Figure 8: Input and Output Velocities

By using the output velocities, a Reynolds number may be calculated using Equation 3-4. Reynolds number identifies each system's relevant level of laminar or turbulent flow. Each system was determined to be turbulent in nature. Table 3 shows the Reynolds number calculated in each system using the assumption that each nozzle has a very small convergence length before exit. The Reynolds number in these systems denotes the turbulent or laminar nature of the streams and will serve as a comparison tool in future analyses.

Table 3: Reynolds Number Values for Systems 1,2 &3

	System 1	System 2	System 3
Reynolds Number	27715	19404	19923

The placement of the nozzle with respect to the load cell was such that maximum output was achieved. The distance between the nozzle and the load cell impact plate was roughly 1 mm. This value was observed to have the highest force ratings across each system and nozzle impact from recoil during the initial release of the streams. Initial testing showed correlations between exit velocity and impact ratings as expected except in the case of system 3. However, upon further inspection it was found that system 3's nozzle opening was higher in the assembly than the others. Where system 1 and system 2 each had a nozzle that opened directly at the impact plate, system 3 had a circular shroud that encased the nozzle and prevented the use of a uniform impact distance. The larger distance from stream exit to impact point results in a drastic pressure loss due to a lack of stream confinement as well as lower pressure air surrounding the stream.[1] Stream degradation was also observed further from the exit point and as such, the value for stream diameter which is observed at the nozzle exit was used for stream diameter.

Force measurements were taken as both peak outputs and sustained values. The peak value was typically observed just after stream initiation and may in fact be caused by backpressure in the system. For instance, systems 2 and 3 show extreme peak output forces, well in excess of the energy available at steady state power consumption. This may be explained by the initial power used to bring the supply reservoir up to output pressure. Essentially, the peak force observed is a result of prior power input. Figure 9 shows the peak output values recorded over the course of 5 trials.

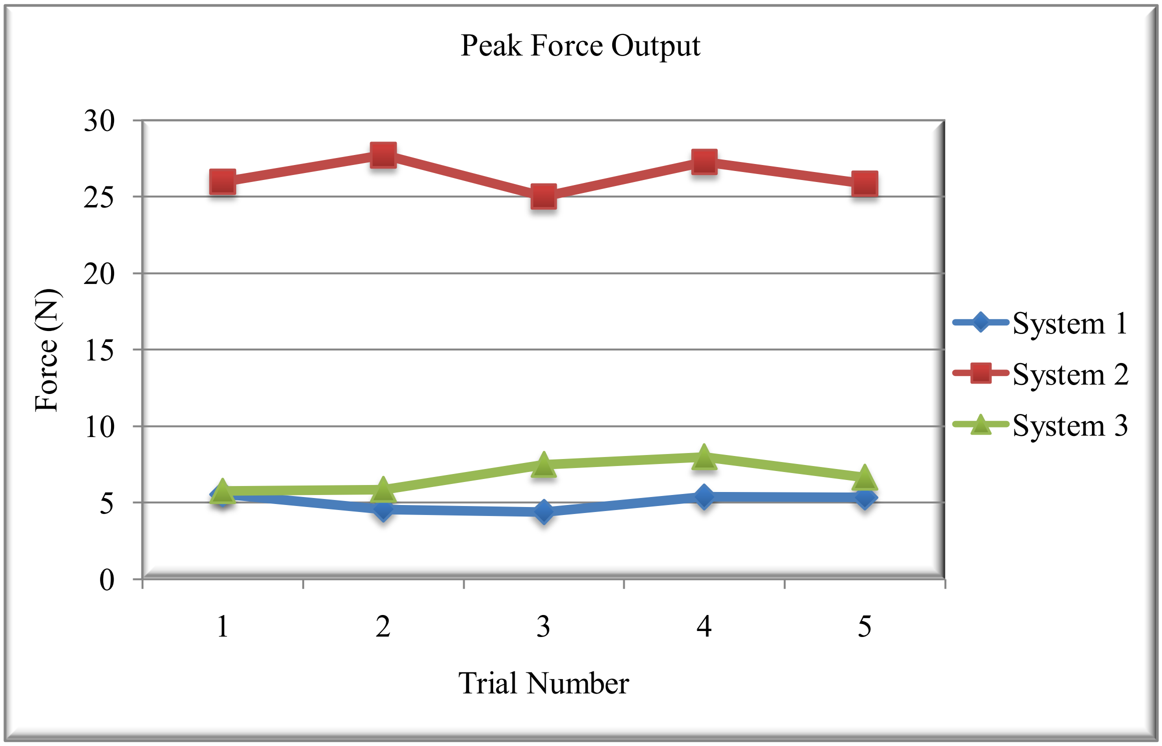

Figure 9: Force Output

Sustained values by comparison were measured on a per unit time basis and compared to both water usage and power usage. Sustained values were shown to be much lower than peak values. Figure 10 shows the average sustained force output in comparison to the average peak force output for all three systems as well as a mode whereby no work was added to the system.

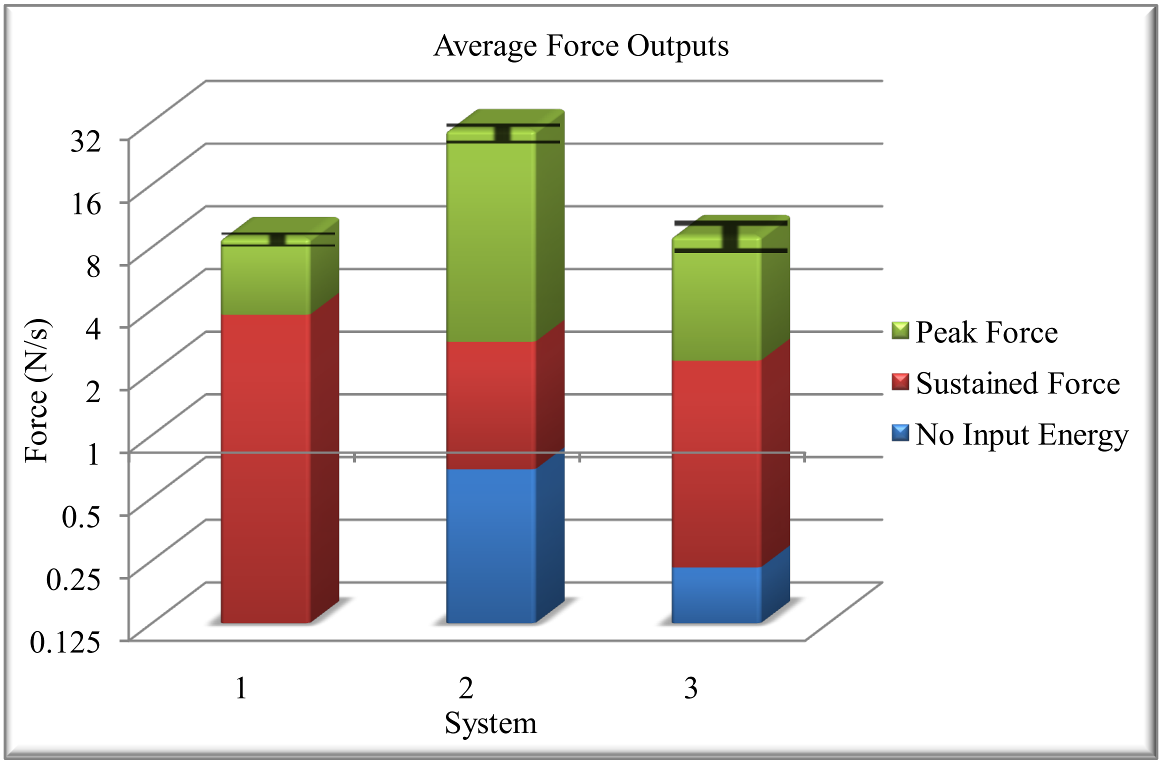

Figure 10: Average Force Outputs

From this particular point, a variety of models exist for determining output pressure. Because the emphasis of this analysis is on impact force, pressure was calculated directly from empirically gathered values. As such, pressure was found by dividing the measured force by the measured stream diameter as defined by Equation 3-3. While this value is almost certainly not the actual output pressure at the nozzle, it was determined to be the most useful value for calculating efficiency. It was also posited that this value would be closest in nature to what can be described as a transmitted pressure associated with the water stream. In other words, this pressure is what a work piece would actually experience regardless of how pressurized the stream may be. By comparison, a secondary value for pressure was also found and defined as the "No Loss

Pressure." This particular value is found by modeling the water stream as a projectile and applying the kinetic energy term in the second half of Equation 3-3 where the velocity term is taken as the velocity out found by the flux equation. A comparison of average peak, average sustained, and no loss pressure values associated with each of the three systems is conveyed in Figure 11.

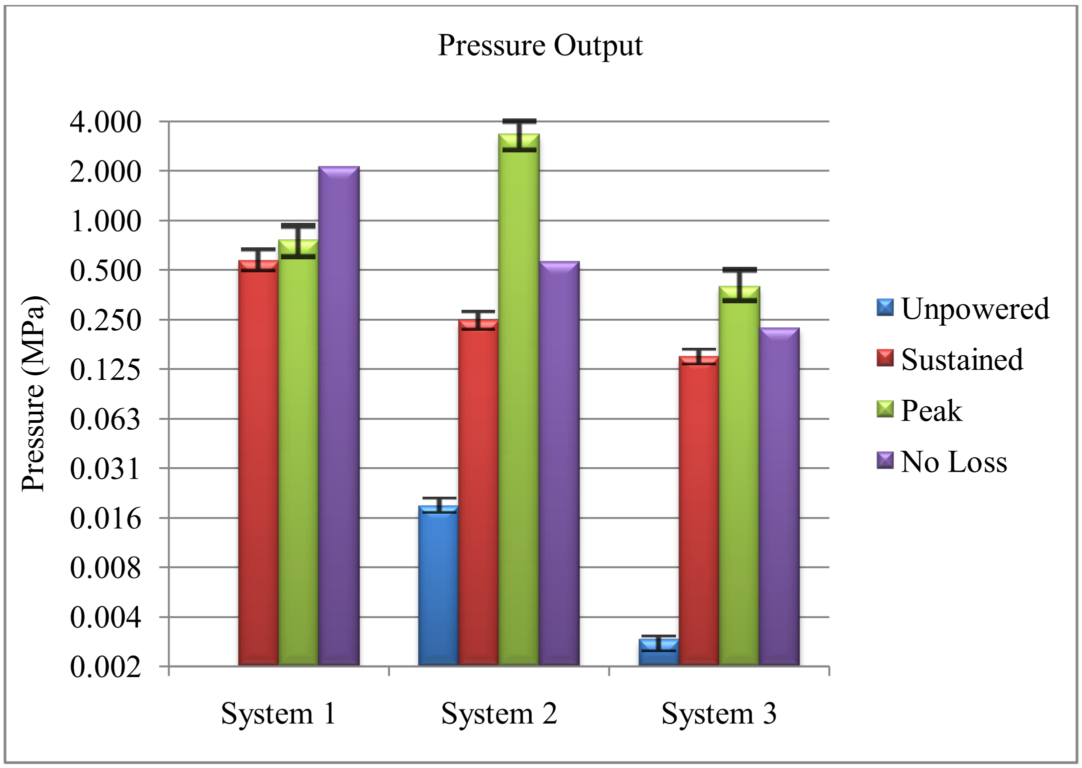

Figure 11: Pressure Output

The velocity and pressure values then allow for the calculation of both kinetic energy and enthalpy terms. Kinetic energy relies upon the difference between entry and exit velocity where as the enthalpy term relies upon the difference between entry and exit internal energy, pressure, and specific volume. Because water is modeled as incompressible, specific volume is taken as constant. Temperature at the inlet and exit was also measured experimentally as constant. The average enthalpy and kinetic energy terms with respect to average power consumption in each system under steady state are made available in Table 4. System 1 was not included because an accurate input pressure value could not be established while maintaining the same volumetric flow rate.

Table 4: Work in, Enthalpy, and Kinetic Energy Values for Systems 2 & 3

	System 2	**System 3**
Work in (J/s)	729.60	1246.00
Enthalpy (J/kg)	249.02	140.47
Kinetic Energy (J/kg)	53.88	28.85

When the kinetic energy and enthalpy terms are combined, the power required can be found, and with it an efficiency value. Because the intent of the study was to develop an analysis which would accurately assess a process in continuous action, the efficiencies were calculated under sustained conditions for systems 2 and 3. System 1 had no direct power input and as such did not qualify to be assessed for efficiency as specified by the established model. Table 5 conveys the average power required, actual power input, and corresponding efficiency.

Table 5: Work In, Work Required, and Efficiency Ratings for Systems 2 & 3

	System 2	System 3
Work in (J/s)	729.60	1246.00
Work required (J/s)	25.00	20.02
Efficiency	3.42%	1.61%

Because the values used were based on the impact or transmittable force rather than that measured directly at the nozzle, the enthalpy term may have in fact been larger. As such, rather than looking at standard efficiencies, a better option may be to look at how much force was imparted by the water stream compared to what a solid object might do. This will be a comparison of the force out term to calculations of what could be an expected force determined from the calculated velocity out which has been designated as the impartment efficiency. Measured force outputs and calculated force outputs are used to define the kinetic energy transmission efficiency (impartment efficiency) and can be found in Table 6.

Table 6: Forces and Impartment Efficiency

	System 1	System 2	System 3
Force Out (N/s)	3.78	2.12	2.22
Calculated Force Out (N/s)	14.06	4.44	3.43
Impartment Efficiency	26.91%	47.79%	64.78%

To determine the effectiveness of the pressure washer, values for internal energy and entropy were determined through the use of water property tables. Through the use of Equation 3-2 enthalpy was calculated using input and output pressures along with the internal energy of the water stream at usage temperature. Entropy was then found using a correlated enthalpy value. Calculation of exergy destruction was done through the manipulation of Equation 2-2. Total exergy is then found by subtracting exergy destruction from the standard work in equation resulting in Equation 3-9. The total exergy defines the total energy available with regard to the base state, in this case the temperature of the room. When compared to the actual input energy, an exergetic efficiency may be found. Figure 12 compares 1st law efficiency (Equation 3-8) to 2nd law effectiveness efficiency (Equation 3-10).

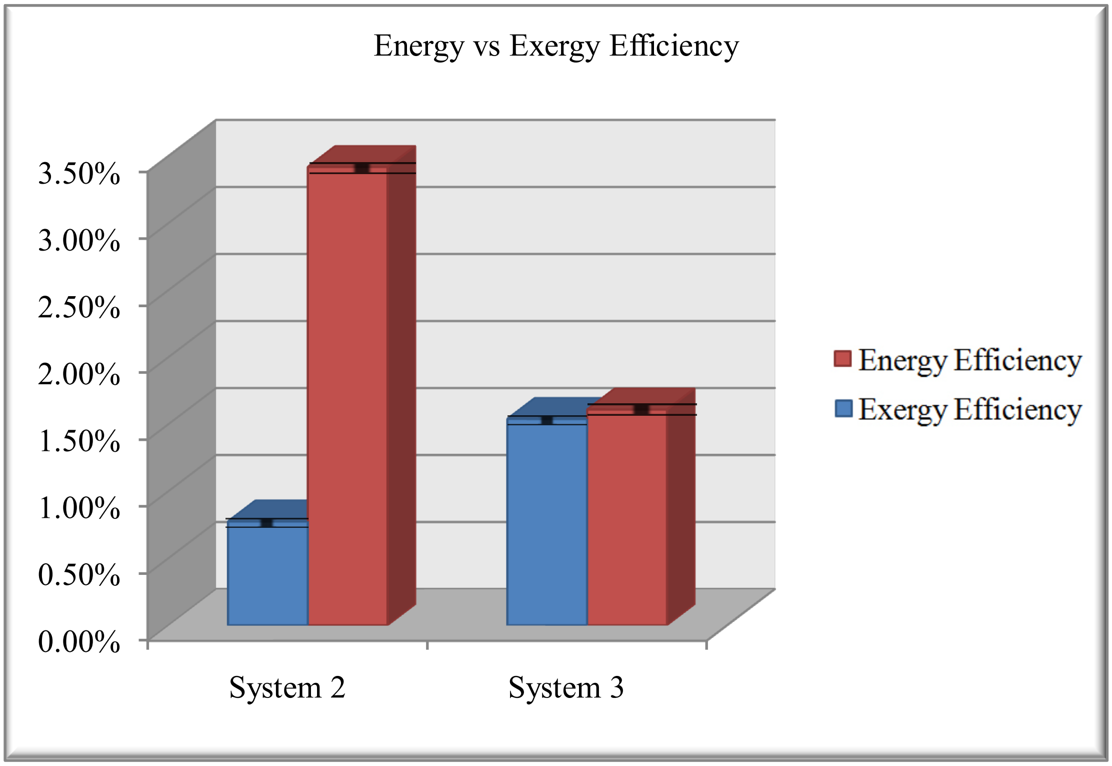

Figure 12: Energy and Exergy Efficiencies of Systems 2 and 3

While each system scales up in terms of cross sectional diameter, the outputs and efficiencies do not. This is of particular interest when examining the nozzle geometries. System 1 has a flat nozzle head similar in nature to the nozzle in system 3. Unfortunately a direct comparison cannot be made because the nozzle to impact distance in system 3 could not be standardized because of the protective shroud. This particular fact comes into play when examining the pressure decrement involved once a turbulent stream becomes unconfined. As each system was calculated as highly turbulent, system 3 in respect suffers from higher levels of degradation than either of the other 2 systems. Fortunately, once steady state was reached, pressures and impact forces were found to be similar in nature to system 2.

Sustained force values showed a decrease which correlated to the calculated output velocities. In other words, as output velocity increased, so too did unpowered force output. When the compressor on the pump was used to increase the pressure on systems 2 and 3, substantial gains in output force were noticed. System 1 remained the highest total force output. As denoted in Table 6, however, the force out efficiency increased as power input increased. This would seem to suggest that increased pressure of a stream results in a higher level of imparted velocity. In other words, the stream begins to act more as a solid beam pushing on the force sensor rather than splashing against it.

Looking at the relatively low imparted kinetic energy efficiency led to the thought of comparing unpowered kinetic impartment efficiency in Table 7. This particular figure conveys how well each nozzle is designed to work without increasing the pressure of the water being used.

Table 7: Unpowered Kinetic Impartment Efficiencies

	System 1	**System 2**	**System 3**
Unpowered Force Out (N/s)	3.78	0.67	0.20
Calculated Force Out (N/s)	14.06	4.44	3.43
Efficiency	26.91%	15.03%	5.70%

Chapter 5: EIO-LCA

The environmental impact of waterjet cutter use was assessed using an Economic Input/Output – Life Cycle Analysis (EIO-LCA) model. The model chosen was designed for the specific case of analyzing processes on a usage or unit time basis. The analysis consists of determining resource requirements and assessing the environmental impact of their use in the process.

The initial step in this analysis is to determine the usage costs associated with the waterjet cutting process. In this respect, the primary costs come from the purchase of the unit, the cost of water on a volumetric basis, and the electricity consumption in kWatts. Table 8 details these costs for each of the three experimental systems tested. The water and electricity consumption values were gathered during the experimental assessment. Electricity costs were provided by Tampa Electric and are a suggested commercial rate. Water costs were provided by the City of Tampa Water Department.

Table 8: Resource Consumption & Costs

	System 1	System 2	System 3
Cost ($)	20.00	200.00	200.00
Water Consumption (gal/hour)	102.84	78.26	112.5
Electricity Consumption (kWh)	0	0.73	1.25
Electricity Cost ($/kWh)	0.128	0.128	0.128
Water Cost ($/gal)	0.005	0.005	0.005

These values then allow for the calculation of total cost per hour of use. Electricity and water costs per hour of usage were calculated by multiplying consumption rate by cost. Annual cost could be calculated if an assumed value for daily or weekly use was given. At this time, that data is not available. Table 9 shows the hourly cost for each system with regard to electricity and water consumption. Interestingly, system 2 which was a powered system showed the lowest total cost per hour at just $

0.48. This also shows that water cost is much higher per hour usage than the electricity required to power the pressure washer. This may not be the case with a waterjet cutter.[17]

Table 9: System Resource Costs Per Hour

	System 1	System 2	System 3
Electricity Cost ($/hour)	0	0.09	0.16
Water Cost ($/hour)	0.51	0.39	0.56
Total Cost ($/hour)	0.51	0.48	0.72

The EIOLCA software assesses impact based on cost sector performance. The intent is to asses, in a specific area, what greenhouse gasses are released as a result of economic activity. In other words, by relating the system usage to cost per hour, the EIOLCA software makes available a per hour greenhouse gas emission and energy consumption value. Higher values are more detrimental to the environment. The emission and consumption values for each system based on water cost for the water, sewage, and other systems sector are designated in Table 10. The calculated emission and power consumption values for each system based on electrical cost assessed in the power generation and supply sector are then available in Table 11. Total global warming potential values and power consumptions for each system are conveyed through Table 12.

Table 10: Water Sector Global Warming Potential & Energy Consumption

	GWP (mt CO_2 equiv.)	**Energy Consumption (TJ)**
System 1	0.000570	0.000001
System 2	0.000436	0.000001
System 3	0.000626	0.000001

Table 11: Power Supply Sector Global Warming Potential & Energy Consumption

	GWP ($mt\ CO_2$ equiv.)	Energy Consumption (TJ)
System 1	0	0
System 2	0.00077	0.000009
System 3	0.001369	0.000016

Table 12: Total Global Warming Potential & Energy Consumption

	GWP Total ($mt\ CO_2$ equiv.)	Total Energy Consumption (TJ)
System 1	0.000570	0.000001
System 2	0.001206	0.000010
System 3	0.001995	0.000017

The distinction between which sectors emit greater amounts of greenhouse gasses is important to notice here. While system 2 had the lowest total cost per hour to run, its green house gas emissions were second highest. This is due in part to the fact that system 1 had no direct power consumption. Power consumption, while cheaper cost per hour in all cases, produced significantly greater amounts of greenhouse gases. As such, it is clearly the case that power supply has a greater negative impact on the environment than water consumption in pressurized water systems such as those tested.

Chapter 6: Discussion

Thermodynamic efficiency and effectiveness analysis serve to demonstrate how well a process or system is performing with respect to the best possible performance obtainable. As detailed in Chapter 2, an effectiveness efficiency which approaches a 1^{st} law efficiency is indicative of a minimal loss of energy in the form of system irreversibilities. Essentially, this means that more of the energy is used and not wasted. In this way, it is acceptable to then say that efficiency measures the losses of energy due to system parameters whereas effectiveness measures how well the energy was used. Increasing entropy of a system typically results in higher losses due to irreversibility and as such lower effectiveness. Such a relationship may prove to show that higher effectiveness may show a lower level of system wastes and by-products.

Determinations of both performance and efficiency in the tested systems led to a marked cap of available impact potentials. The meaning behind this is in the fact that velocity output remains constant thus establishing the maximum kinetic energy output available to the system. There are potential differences in actual force output compared to maximum force output as a result of stream pressurization. This effectively shows that while impartment efficiency increases under higher power input, further output could be achieved through the use of better nozzle geometry, most namely lower cross sectional area which tends to result in higher output velocity as defined by Equation 3-7. Since only systems 2 and 3 were able to use the pump, an assessment of the two systems from unpowered to powered may allow for the reasonable extrapolation of how system 1 would react under pressurized conditions. Both system 2 and 3 showed higher impartment efficiencies using pressurized water. As such, system 1 would most likely show an increase in impartment efficiency. Further testing may show that the more efficient nozzle designs of system 1 and 3 could show even higher impartment efficiencies under pressurized conditions if nozzle-to-impact distance was able to be standardized. System 3 would have to be modified to allow for those conditions.

The idea behind increased impartment efficiency with decreasing energy efficiency due to stream turbulence may allow for an optimization to be associated with a system. In order to further explore this, a system with variable pressure would have to be utilized. A relationship between power input efficiency and the corresponding imparted energy efficiency may then be investigated.

Furthermore, reducing the Reynolds number of each stream or even allowing the stream to become fully developed may increase impartment efficiency, 1st law efficiency, and effectiveness. The idea behind this is that a more cohesive stream tends to impart more of the energy stored within as seen with system 1 which had the smallest stream and a nozzle designed to reduce diffusion after exiting. This could be done by increasing the length of the nozzle to an extent which would allow for the stream to become more fully developed as is the case with modern waterjet cutter nozzles.

6.1. Tradeoffs Between Performance and LCA

Based on the model assessment, a correlation can also be found between increasing pressure and power requirements. This would seem to imply that increasing pressure serves to not only significantly increase losses due to irreversibilities, but also to increase the negative impact of the process from a global warming perspective. However, manipulation of equation 3-6 also shows that increased exit velocities may be obtained by reduction in cross-sectional area. This is in fact why system 2 had the lowest cost per hour to run but still had the highest sustained force output between the powered systems. The lower resource cost per hour then correlated to a lower green house gas emission value. Therefore, it should be a focus to reduce water and electricity consumption while increasing exit velocity in order to create the highest force output.

6.2. Cell Analogy

In thermodynamic analysis of a system or cycle, boundaries are established in order to delimit the areas or components to be considered. This is done to establish independent analytical values for the component or device within the boundaries. As such, full analysis may be done starting at component level and moving upward in scale through the level of full system. This is typically done to assess how each component, sub assembly, or assembly affects the system as a whole. Often there are concerns about the effect of any change upon both the local and global efficiencies. Parts of the system can be targetted for design refinements aimed at increasing efficiency, performance, or utility.

In this case, an organelle may be assessed which is a basic component of a cell which is in turn a basic component of an organ. The organelle, as a component to the entire system, would then be a factor in the overall system's performance and efficiency ratings. Such dileneations would then prove useful in comparing similar levels of scale in the biological system to that of a thermodynamic system.

Analyzing a biological process in the terms a thermodynamic model requires that all inputs and outputs be quantified to determine all forms of mass and energy entering and exiting the boundaries of the system. Establishment of such parameters has been done on a series of processes with increasing complexity whereby each more complex system makes use of the systems before it. In this case, the most complex system, the heart, makes use of muscle cells for contraction, which are fueled by ATP created in mitochondria. The various inputs and outputs of each system are made available in Table 13.

Table 13: Thermodynamic analysis of 3 biological systems

	Mitochondria[19] **(organelle)**	**Muscle Cell** [20,21] **(cell)**	**Heart**[22] **(organ)**
Input	Glucose,6 O2, 36 Phosphate, 36 ADP	Creatine Phosphate, Glycogen, ATP	75% Oxygen rich blood, O2(pulmonary stage), Contraction by cardiac muscle cells
Output	6 CO2, 6 H2O, 36 ATP	Contractive force, waste products from ATP generation	97% Oxygen rich blood, waste products from muscle cells and mitochondria
Gibbs Free Energy Efficiency	50%	15 - 35%	15 - 25%
Comparison	Energy conversion	External work	Change in stream energy

A relation can then be drawn that as a greater number of energy interactions occur a lower Gibbs free energy efficiency is obtained. When compared to systems 2 and 3 of the experimental assessment a similarity is also found. System 3 used a much greater amount of energy than system 2 and subsequently had a lower exergy efficiency. Because exergy efficiency and Gibbs free energy efficiency differ only in the reference states, this becomes an adequate manner for comparison. However, biological systems are not assessed for 1st law efficiency values and as such, nothing can be said of the comparison between how effectively the energy was utilized and if there are trends similar in the mechanical processes. Further research in this area could lead to the determination of relationships between efficiency and effectiveness of biological systems and would then allow for their comparisons to mechanical systems.

The end result of adaptation and evolution achieved by a biological system, in most cases the survivability in a set of environmental parameters, may lead toward an understanding regarding designing processes with higher effectiveness as a goal. The typical assessment of biological processes is done at a reference state of system temperature. Changing the reference state of the biological system's analysis from system temperature to ambient temperature would also serve to strengthen this argument if the same trends were found as those between exergy efficiency and Gibbs free energy with changes in complexity and energy usage types.

Chapter 7: Conclusions

The energy-exergy efficiency model with the experimental validation provide the following insight into waterjet design:

- Nozzle geometry, cross sectional area and design, greatly impact stream cohesion, impartment force, and to an extent regulate environmental impact.
- Higher impartment efficiencies were nearly always the result of increased pressurization of the water stream but tended to reduce 1^{st} law efficiency. Increasing pressure caused the water to impart the impact surface with kinetic energy more closely equivalent to expected values.
- Higher exit velocity has a much greater impact on force output than mass flow rate.
- Water consumption, while much more costly than electricity, results in substantially lower amounts of negative environmental impact.

In comparison with biological systems at different scales, the following determinations were made:

- Biological systems showed reductions in 2^{nd} law efficiency as complexity increased similar to mechanical systems.
- Biological systems have higher 2^{nd} law efficiencies at optimum reaction temperatures. This should be explored in manufacturing processes.

Further recommendations:

- Further comparison between other biological systems at the same scale could lead to more efficient and effective system design practices.
- Testing at supersonic stream speeds could result in different conclusions and should be examined.
- Calculate ΔG values using ambient temperatures rather than system temperature and determine if there is an applicable effect on Gibbs free energy efficiency.
- Determine 1st law efficiency of cellular and biological processes for comparison with Gibbs free energy efficiency which will allow for direct comparison to mechanical processes.

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Appendices

Appendix 1: Experimental Assessment Photos

Figure 13: Volumetric Flow Meter (Gal)

Appendix 1 (Continued)

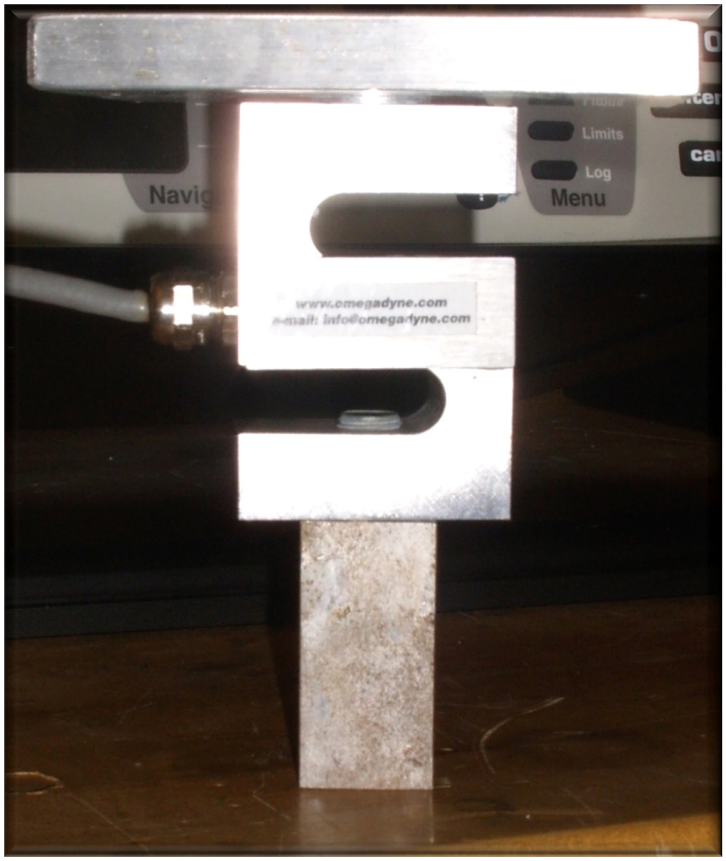

Figure 14: Load Cell With Impact Plate & Mount

Figure 15: Input Line Pressure Meter (psi)

Appendix 1 (Continued)

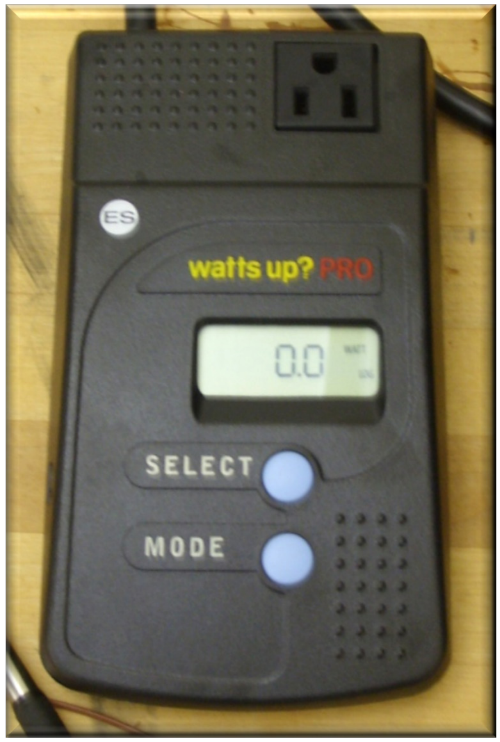

Figure 16: Watts Up Electricity Meter

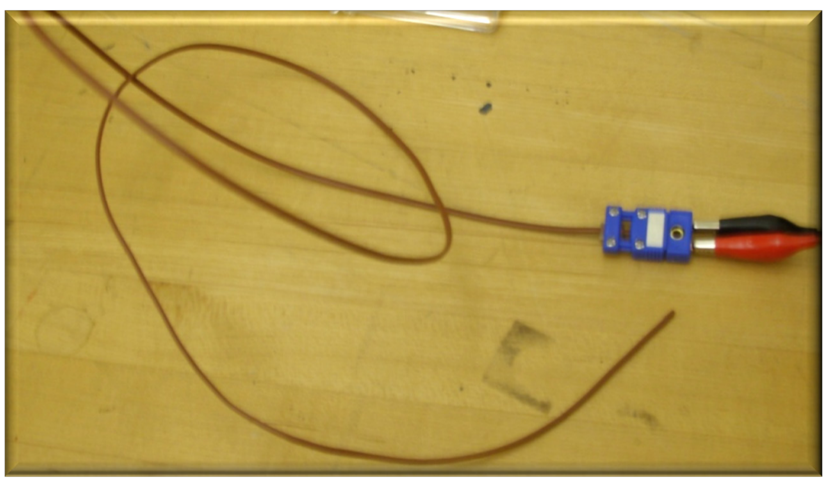

Figure 17: Type J Thermocouple

Appendix 1 (Continued)

Figure 18: Nozzle Comparison for Each System

Figure 19: System Comparison

Appendix 1 (Continued)

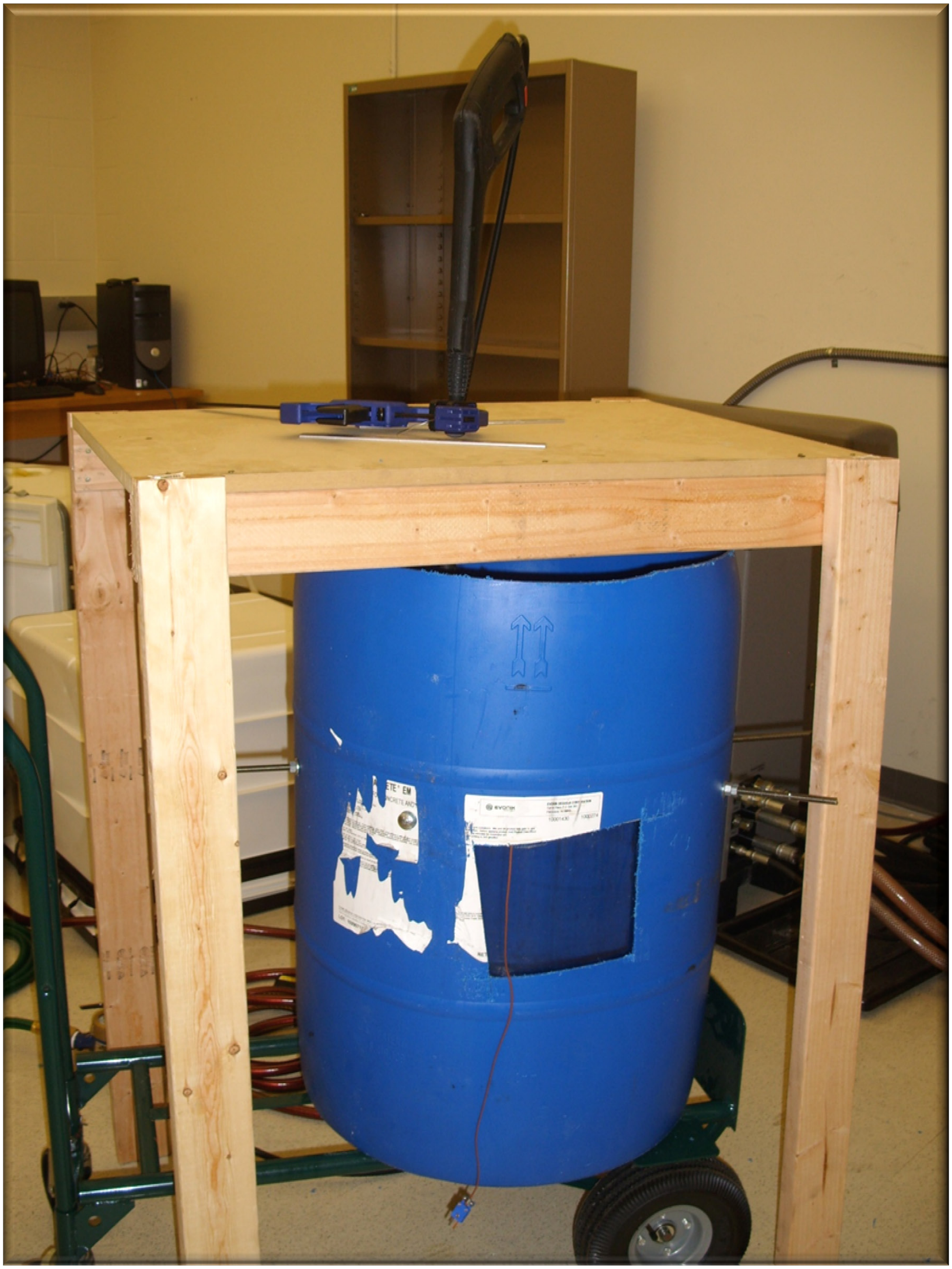

Figure 20: Experimental Test Stand Assembly

Appendix 2: Experimental Data

Specific Volume (ft^3/lb)		Pressure In (lb/in^2)		Pressure In (Pa)
0.016023073		80		551580.583
Specific Volume (m^3/kg)		Kinematic Viscosity		Temp Surround (C)
0.001000288		0.0000017		21.41
Water Cost ($/gal)				
0.005372751		Jet Ratio	Turbo Ratio	Adjustable Ratio
		29.536862	25	12.75510204
Electric Cost ($/kWh)				
0.12844				

1800 PSI (Pa)	Area in (in^2)	Area in (m^2)
12410563.1	0.306919643	0.000198012

Appendix 2 (Continued)

	Trial	Diameter (in)	Diameter (m)	Area (in^2)
Jet	1	0.115	0.002921	0.010391071
	2	0.115	0.002921	0.010391071
	3	0.115	0.002921	0.010391071
	4	0.115	0.002921	0.010391071
	5	0.115	0.002921	0.010391071
Pressure Washer Turbo	1	0.125	0.003175	0.012276786
	2	0.125	0.003175	0.012276786
	3	0.125	0.003175	0.012276786
	4	0.125	0.003175	0.012276786
	5	0.125	0.003175	0.012276786
Pressure Washer Adjust	1	0.175	0.004445	0.0240625
	2	0.175	0.004445	0.0240625
	3	0.175	0.004445	0.0240625
	4	0.175	0.004445	0.0240625
	5	0.175	0.004445	0.0240625

Appendix 2 (Continued)

	Trial	Area (m^2)	Mass Flow Rate (lb/s)	Mass Flow Rate (Kg/s)	Temp (C)
Jet	1	6.7E-06	0.238332	0.108105	38.1
	2	6.7E-06	0.238332	0.108105	38.1
	3	6.7E-06	0.238332	0.108105	38.1
	4	6.7E-06	0.238332	0.108105	38.1
	5	6.7E-06	0.238332	0.108105	38.1
Pressure Washer Turbo	1	7.92E-06	0.181369	0.082268	38.1
	2	7.92E-06	0.181369	0.082268	38.1
	3	7.92E-06	0.181369	0.082268	38.1
	4	7.92E-06	0.181369	0.082268	38.1
	5	7.92E-06	0.181369	0.082268	38.1
Pressure Washer Adjust	1	1.55E-05	0.260718	0.11826	38.1
	2	1.55E-05	0.260718	0.11826	38.1
	3	1.55E-05	0.260718	0.11826	38.1
	4	1.55E-05	0.260718	0.11826	38.1
	5	1.55E-05	0.260718	0.11826	38.1

Appendix 2 (Continued)

	Trial	Internal Energy (kJ/kg)	Exergy Destruction (J/s)	In Enthalpy (kJ/kg)	Out Enthalpy (kJ/kg)	Isentropic Pressure Out (lb/in^2)
Jet	1	159.2		159.7517	159.8173	304.2759
	2	159.2		159.7517	159.731	304.2759
	3	159.2		159.7517	159.6912	304.2759
	4	159.2		159.7517	159.8173	304.2759
	5	159.2		159.7517	159.7668	304.2759
		Avg		159.7517	159.7647	304.2759
		std dev		0	0.054945	0
Pressure Washer Turbo	1	159.2	22.86975	159.2189	159.5146	81.30888
	2	159.2	21.76147	159.2164	159.4977	81.30888
	3	159.2	19.63248	159.2215	159.4753	81.30888
	4	159.2	14.88437	159.2126	159.405	81.30888
	5	159.2	17.16662	159.2253	159.4472	81.30888
		Avg	19.26294	159.2189	159.468	81.30888
		std dev	3.276992	0.004809	0.043315	0
Pressure Washer Adjust	1	159.2	0.90819	159.2032	159.3634	32.07691
	2	159.2	0.618026	159.2019	159.329	32.07691
	3	159.2	0.763108	159.2045	159.3376	32.07691
	4	159.2	0.980731	159.2032	159.3433	32.07691
	5	159.2	0.806633	159.2013	159.3433	32.07691
		Avg	0.815338	159.2028	159.3433	32.07691
		std dev	0.139384	0.001256	0.012657	0

Appendix 2 (Continued)

	Trial	Isentropic Pressure Out (Pa)	Gun Pressure Out (lb/in^2)	Gun Pressure Out (Pa)	Peak Pressure Out (lb/in^2)	Peak Pressure Out (Pa)
Jet	1	2097876	-	-	120.2975	829408.9
	2	2097876	-	-	99.12511	683432.9
	3	2097876	-	-	95.27559	656891.8
	4	2097876	-	-	116.4479	802867.8
	5	2097876	-	-	115.8705	798886.6
	Avg	2097876			109.4033	754297.6
	std dev	0			11.35086	78260.2
Pressure Washer Turbo	1	560596.2	2.746799	18938.22	475.702	3279798
	2	560596.2	2.380559	16413.12	457.7817	3156244
	3	560596.2	3.113039	21463.32	499.3242	3442665
	4	560596.2	1.8312	12625.48	473.2583	3262950
	5	560596.2	3.662399	25250.96	461.8545	3184325
	Avg	560596.2	2.746799	18938.22	473.5841	3265197
	std dev	0	0.6973	4807.639	16.23609	111942.1
Pressure Washer Adjust	1	221159.1	0.467143	3220.786	38.23436	263612.5
	2	221159.1	0.280286	1932.471	51.94886	358169.2
	3	221159.1	0.654	4509.1	54.02682	372496
	4	221159.1	0.467143	3220.786	54.858	378226.7
	5	221159.1	0.186857	1288.314	74.80636	515763.7
	Avg	221159.1	0.411086	2834.291	54.77488	377653.6
	std dev	0	0.182126	1255.693	13.07098	90119.81

Appendix 2 (Continued)

		Sustained	Sustained	Isentropic A1*Vel1 = A2*Vel2	Peak F=1/2mv^2
	Trial	Pressure Out (lb/in^2)	Pressure Out (Pa)	Velocity Out (m/s)	Velocity Out (m/s)
Jet	1	89.50131	617080.2	16.13039216	10.14236874
	2	76.99037	530821.7	16.13039216	9.206679013
	3	71.2161	491010	16.13039216	9.026138369
	4	89.50131	617080.2	16.13039216	9.978771425
	5	82.18722	566652.1	16.13039216	9.953999923
	Avg	81.87926	564528.8	16.13039216	9.661591495
	std dev	7.966969	54929.46	0	0.50695133
Pressure Washer Turbo	1	45.61526	314501.2	10.38966983	25.13044796
	2	43.17158	297652.9	10.38966983	24.65255659
	3	39.91335	275188.6	10.38966983	25.7468465
	4	29.73137	204987.4	10.38966983	25.06581747
	5	35.84056	247108.1	10.38966983	24.76197815
	Avg	38.85442	267887.6	10.38966983	25.07152934
	std dev	6.280555	43302.23	0	0.427468538
Pressure Washer Adjust	1	23.68868	163325.2	7.619969937	8.319245279
	2	18.70159	128940.9	7.619969937	9.69717028
	3	19.94836	137537	7.619969937	9.889212097
	4	20.77954	143267.7	7.619969937	9.964992608
	5	20.77954	143267.7	7.619969937	11.63660434
	Avg	20.77954	143267.7	7.619969937	9.90144492
	std dev	1.8352	12653.06	0	1.178987911

Appendix 2 (Continued)

Sustained
F=1/2mv^2

	Trial	Velocity Out (m/s)	Velocity in Gun (m/s)	Velocity in (m/s)	Power In (Watts)
Jet	1	8.7483442		0.546111	0
	2	8.113895		0.546111	0
	3	7.8036943		0.546111	0
	4	8.7483442		0.546111	0
	5	8.3832675		0.546111	0
	Avg	8.3595091		0.546111	0
	std dev	0.409941		0	0
Pressure Washer Turbo	1	7.781939	4.027536	0.415587	728
	2	7.5706251	3.749432	0.415587	729
	3	7.2793374	4.28764	0.415587	727
	4	6.282612	3.288469	0.415587	731
	5	6.8979516	4.650598	0.415587	733
	Avg	7.162493	4.000735	0.415587	729.6
	std dev	0.5933192	0.518611	6.21E-17	2.408319
Pressure Washer Adjust	1	6.548283	1.939434	0.597406	1250
	2	5.8183022	1.502279	0.597406	1245
	3	6.0091166	2.294769	0.597406	1243
	4	6.133029	1.939434	0.597406	1240
	5	6.133029	1.226606	0.597406	1252
	Avg	6.128352	1.780504	0.597406	1246
	std dev	0.2677377	0.41809	0	4.949747

Appendix 2 (Continued)

	Trial	Peak Force Out (lbf)	Peak Force Out (N)	Sustained Force Out (lbf)	Sustained Force Out (N)	Gun Force Out (lbf)
Jet	1	1.25	5.560277	0.93	4.136846	
	2	1.03	4.581668	0.8	3.558577	
	3	0.99	4.403739	0.74	3.291684	
	4	1.21	5.382348	0.93	4.136846	
	5	1.204	5.355659	0.854	3.798781	
	Avg	1.1368	5.056738	0.8508	3.784547	
	std dev	0.117946	0.524649	0.082784	0.368242	
Pressure Washer Turbo	1	5.84	25.97761	0.56	2.491004	0.15
	2	5.62	24.99901	0.53	2.357557	0.13
	3	6.13	27.2676	0.49	2.179629	0.17
	4	5.81	25.84417	0.365	1.623601	0.1
	5	5.67	25.22142	0.44	1.957218	0.2
	Avg	5.814	25.86196	0.477	2.121802	0.15
	std dev	0.199324	0.886637	0.077104	0.342975	0.038079
Pressure Washer Adjust	1	0.92	4.092364	0.57	2.535486	0.05
	2	1.25	5.560277	0.45	2.0017	0.03
	3	1.3	5.782688	0.48	2.135146	0.07
	4	1.32	5.871653	0.5	2.224111	0.05
	5	1.8	8.006799	0.5	2.224111	0.02
	Avg	1.318	5.862756	0.5	2.224111	0.044
	std dev	0.314516	1.399035	0.044159	0.196428	0.019494

Appendix 2 (Continued)

	Trial	Gun Force Out (N)	No Loss Force Out (N)	Peak D Enthalpy	Peak KE	Peak Work In Calculated (Watts)
Jet	1		14.06396	277.9083	129.9457	44.09124
	2		14.06396	131.8903	129.9457	28.3059
	3		14.06396	105.3416	129.9457	25.43583
	4		14.06396	251.3596	129.9457	41.22118
	5		14.06396	247.3772	129.9457	40.79067
	Avg		14.06396	202.7754	129.9457	35.96896
	std dev		1.99E-15	78.28274	0	8.462791
Pressure Washer Turbo	1	0.667233	4.440198	3261.799	53.88626	272.7735
	2	0.578269	4.440198	3140.736	53.88626	262.8138
	3	0.756198	4.440198	3422.187	53.88626	285.9682
	4	0.444822	4.440198	3251.261	53.88626	271.9065
	5	0.889644	4.440198	3159.984	53.88626	264.3974
	Avg	0.667233	4.440198	3247.193	53.88626	271.5719
	std dev	0.169383	0	111.57	7.94E-15	9.178598
Pressure Washer Adjust	1	0.222411	3.433309	260.4667	28.85352	34.2149
	2	0.133447	3.433309	356.3393	28.85352	45.55275
	3	0.311376	3.433309	368.0929	28.85352	46.94272
	4	0.222411	3.433309	375.1139	28.85352	47.77302
	5	0.088964	3.433309	514.6235	28.85352	64.27137
	Avg	0.195722	3.433309	374.9273	28.85352	47.75095
	std dev	0.086712	4.97E-16	90.84122	0	10.74285

Appendix 2 (Continued)

	Trial	Peak Work Efficiency	Peak Vel Efficiency	Peak Vel^2 Efficiency	Peak KE Efficiency	Peak Re
Jet	1	#DIV/0!	62.87738	39.53566	39.53566	27715.81
	2	#DIV/0!	57.0766	32.57738	32.57738	27715.81
	3	#DIV/0!	55.95734	31.31224	31.31224	27715.81
	4	#DIV/0!	61.86317	38.27051	38.27051	27715.81
	5	#DIV/0!	61.7096	38.08074	38.08074	27715.81
	Avg	#DIV/0!	59.89682	35.95531	35.95531	27715.81
	std dev	#DIV/0!	3.142833	3.73045	3.73045	0
Pressure Washer Turbo	1	37.46888	241.8792	585.0554	585.0554	19404.24
	2	36.05128	237.2795	563.0156	563.0156	19404.24
	3	39.33538	247.812	614.1078	614.1078	19404.24
	4	37.19651	241.2571	582.0499	582.0499	19404.24
	5	36.07058	238.3327	568.0246	568.0246	19404.24
	Avg	37.22453	241.3121	582.4507	582.4507	19404.24
	std dev	1.343901	4.114361	19.96841	19.96841	0
Pressure Washer Adjust	1	2.737192	109.1769	119.1959	119.1959	19923.98
	2	3.658855	127.26	161.951	161.951	19923.98
	3	3.776566	129.7802	168.429	168.429	19923.98
	4	3.852663	130.7747	171.0202	171.0202	19923.98
	5	5.133496	152.7119	233.2094	233.2094	19923.98
	Avg	3.831755	129.9407	170.7611	170.7611	19923.98
	std dev	0.855274	15.47234	40.74887	40.74887	0

Appendix 2 (Continued)

	Trial	Sustained D Enthalpy	Sustained KE	Sustained Work In Calculated (Watts)	Work in - Exergy (Watts)	Exergy Efficiency
Jet	1	65.51847	129.9457	21.13074		
	2	-20.7649	129.9457	11.80304		
	3	-60.588	129.9457	7.497943		
	4	65.51847	129.9457	21.13074		
	5	15.07589	129.9457	15.67762		
	Avg	12.95199	129.9457	15.44802		
	std dev	54.94528	0	5.939885		
Pressure Washer Turbo	1	295.6481	53.88626	28.75535	5.885601	0.808462
	2	281.3208	53.88626	27.57668	5.815211	0.797697
	3	253.7983	53.88626	25.31247	5.679994	0.781292
	4	192.4173	53.88626	20.2628	5.378432	0.735764
	5	221.921	53.88626	22.69	5.523382	0.753531
	Avg	249.0211	53.88626	24.91946	5.656524	0.775349
	std dev	42.36323	7.94E-15	3.485121	0.208129	0.030308
Pressure Washer Adjust	1	160.1505	28.85352	22.35154	21.44335	1.715468
	2	127.045	28.85352	18.4365	17.81847	1.431203
	3	133.0662	28.85352	19.14856	18.38545	1.479119
	4	140.0872	28.85352	19.97887	18.99813	1.532108
	5	142.0203	28.85352	20.20746	19.40083	1.549587
	Avg	140.4738	28.85352	20.02458	19.20925	1.541497
	std dev	12.49918	0	1.478148	1.386125	0.107791

Appendix 2 (Continued)

	Trial	Sustained Work Efficiency	Sustained Vel Efficiency	Sustained Vel^2 Efficiency	Sustained KE Efficiency
Jet	1		54.23516	29.41453	29.41453
	2		50.30191	25.30282	25.30282
	3		48.37883	23.40511	23.40511
	4		54.23516	29.41453	29.41453
	5		51.97188	27.01076	27.01076
	Avg		51.82459	26.90955	26.90955
	std dev		2.54142	2.618338	2.618338
Pressure Washer Turbo	1	3.949911	74.90073	56.1012	56.1012
	2	3.782809	72.86685	53.09578	53.09578
	3	3.48177	70.06322	49.08855	49.08855
	4	2.771929	60.46979	36.56596	36.56596
	5	3.095498	66.3924	44.07951	44.07951
	Avg	3.416384	68.9386	47.7862	47.7862
	std dev	0.48515	5.710664	7.724316	7.724316
Pressure Washer Adjust	1	1.788123	85.93581	73.84964	73.84964
	2	1.480843	76.35597	58.30235	58.30235
	3	1.540512	78.86011	62.18917	62.18917
	4	1.611199	80.48626	64.78038	64.78038
	5	1.614015	80.48626	64.78038	64.78038
	Avg	1.606938	80.42488	64.78038	64.78038
	std dev	0.115335	3.513631	5.721249	5.721249