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Exergy Modeling to Compare Engineered Products to Biological Systems for Sustainable Design

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by

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NOMENCLATURE

B, Ex, Φ	exergy (kJ)
η_B, η_{EX}, ε	exergy efficiency
v	stoichiometric number
$\Delta_f G$	Gibbs energy of formation from the elements (kJ/mol)
T	temperature (°C, K)
EF	energy factor
M	sum of machine electrical energy per cycle
W	water heating energy consumption per cycle
Q	heat transfer rate (W)
k	thermal conductivity (W/m-k)
A	area perpendicular to heat transfer (m^2)
t	thickness parallel with heat transfer (m)
x	quality
m	mass (kg)
u	specific internal energy (kJ/kg)
T_0	dead state / reference temperature (°C, K)
s	specific entropy (kJ/kg-K)
w	work (kJ)
I	irreversibility, exergy consumption (kJ)
σ	entropy production (kJ/kg-K)
v_m	mean specific volume of the liquid
p_b, p_e	initial and final pressure of the liquid
η_m, η_i	mechanical efficiency of the pump and efficiency of fluid compression

Subscripts

k	kinetic energy
p	potential energy
ph	physical energy
ch	chemical energy
th	thermal energy
f	property of saturated liquid
g	property of saturated gas
fg	difference in property of gas and liquid
HT	heat transfer

Superscripts

0	chemical standard conditions
0'	biochemical standard conditions
Θ	intracellular conditions

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ABSTRACT

An ambitious and novel approach to engineering design and sustainability has been taken to explore the potential of drawing parallels between mechanical and biological systems for the possible development of sustainable engineering design metrics using a thermodynamic model. This approach looks to biology. Natural selection has given biological beings and processes high exergetic efficiencies, even while being only 30-40% energy efficient on the cell level. This energy inefficiency, resulting in a release of heat, can then be used to aid in driving other biochemical processes. The Gibbs free energy becomes more negative proportionally with an increase in temperature, resulting in a more favorable reaction. This effective use of waste heat from cell processes actually results in an increase in overall efficiency of an organism, around 50-60%.

As in all systems the boundary defines the analysis. An exergy analysis was conducted on a residential dishwashing machine in several boundary configurations in

order to develop an appropriate model. Exergy serves as a tool for identifying and quantifying losses in the system so that future works can be aimed at reducing irreversibilities. This model was then compared to data previously available regarding exergy within various processes of a biological cell. In future work, it is this comparison, which can be used to develop metrics for use early in the design stage to more efficiently use available and sustainable resources. There is a large difference between the two systems, with the dishwasher only having an effectiveness of 1.3%.

CHAPTER 1: INTRODUCTION

As stated by the Brundtland Commission, sustainability is defined as "the development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[1] With society increasingly moving toward a sustainable lifestyle, products and mechanical systems are in the process of being redesigned to better use materials and energy. The issue that this transformation poses is: how do we design a product to have the same or better functionality while, at the same time, reducing material and energy wastes, without drastically increasing the cost? The solution to this question is one engineers are working towards in terms of trade-offs and multiple objectives.

1.1. Objective

The purpose of this research is to explore the potential of drawing parallels between mechanical and biological systems for the possible development of sustainable engineering design metrics. Of particular interest is how each system makes use of available resources to perform the desired functions and what the implications are for the efficient and effective use of those resources, including the degree of waste generation. Thermodynamic models will be used for comparisons between current, published findings pertaining to cellular processes and a set of experimental data collected from a dishwasher. Metrics serve as a way to quantify certain aspects of engineering design, something a simple set of principles or guidelines cannot do.

1.2. Motivation

Currently the mainstream form of process and product analysis is centered around the Life Cycle Analysis, LCA. The life cycle of a product includes its cradle-to-grave resource use. The purpose of the analysis is to examine the effects the product has on the environment from both an energy and resource perspective. For example: How much energy and materials A, B, and C are required to make the product?, During its operational time, how much energy and resources, such as water, will it use?, Can the product be remanufactured or recycled?, How much energy will it take to process the product at end of life?, and What is this product's overall impact on the environment?

Scientists and engineers have turned to nature for design ideas and guidance all through recorded history. Franco Lodato, a well known visionary and designer, having worked for DuPont, Gillette, and Motorola, has been using the influences of nature in his designs for his entire career.[2]

For the purposes of this research, mammalian cells were selected to compare with the mechanical system. Mammalian cells are considered to be relatively efficient machines, having efficiencies typically ranging between 30-40%. [3][4] The cell is able to operate with minimal waste since most byproducts are reused at some point, either within the particular cell or transported and used in a different cell somewhere else within the organism.[3]

The mechanical system used in this comparative study is a dishwasher. A dishwasher was chosen because of its common place in households, its significant water and electrical energy usage, and very defined inputs and outputs. The basic idea was chosen to investigate a widespread, easy to associate with system that was known to be ineffective in its use of water and energy.

1.3. Scope

In order to evaluate how well the dishwasher makes use of the resources (energy, water), a thermodynamic exergy model has been constructed. Exergy, or availability, is simple in concept, but presents difficulties in application. As will be seen in later sections, exergy analyses are capable of highlighting places for improvement; however, they are not always able to provide guidance on how to make that improvement. This model is then used to develop a quantifiable means of analyzing how effectively the dishwasher is capable of heating the water used in cleaning the dishes.

The models associated with the cell are constructed from researched data. This approach was taken in order to be able to draw relevant, supported conclusions from a biochemical field of study in a mechanical engineering setting.

This paper is focused on the comparison and contrast of these two relative models. Conclusions can then be drawn based on energy and material use, effectiveness of use, and waste.

1.4. Contributions

The primary contribution of this research is to develop basic thermodynamic models for both the biological and mechanical systems and use that comparison, or analogy, to investigate the feasibility of identifying parameters suitable for sustainable engineering design metrics.

1.5. Research Approach

An extensive literature search was conducted to determine the current state of knowledge concerning the thermodynamic behavior of the biological cell, the availability of data for the life cycle analysis, exergy analysis of both the cell and the dishwasher, and the issues directed as sustainability principles for engineering design. An exergy model was then developed as presented in chapter three for use in the experimental testing. Chapters four and five will then respectively present the findings based on the experimental data and discuss these findings. The thesis will then conclude with chapter six, the conclusion. It is in this chapter that suggestions for future work will be made, and comment will be given regarding using the information presented in the thesis for future work in sustainable design.

CHAPTER 2: BACKGROUND

This chapter is presented in order to establish an understanding of terms and principles to be used in subsequent chapters. The scope of this thesis is rooted in mechanical engineering principles; however, there will be information provided relevant to the biological aspect of the comparison.

2.1. Sustainability

The increased realization of the environmental and society impacts of material and energy utilization has led to an aroused awareness that measures must be taken to reduce waste and increase the recycling of spent materials. This awareness has keyed the term "sustainability" and has made it a widespread term in modern developed society. Toolkits for sustainability are even being incorporated into popular design software, such as SolidWorks.

As previously stated, sustainability is a broad term used to describe designing to decrease environmental impact both in the present and the future. Another term that has arisen dealing with sustainability in a more technical way is "Green Engineering."[5] This concept has led to an increase in engineers designing not just for performance, but also with the environmental impact in mind. They now need to consider all aspects of the product, including its material and energy use, as well as the material used in the construction of the product. Anastas and Zimmerman have published their twelve principles of "Green Engineering." They are:

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. Separation 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.

It is this sustainable approach that has led engineers to seek alternate design methods and metrics, in order to maximize their effective output, but at the same time decrease the environmental "footprint." Two methods discussed in this thesis include the "Life Cycle Assessment," which looks at the environmental impact throughout the entire construction, operation and end-life of a product, and exergy, or how effective energy is used within a system. These two approaches do not tell engineers how to design better; however, they do highlight areas in need of improvement.

2.2. Life Cycle Assessment (LCA)

The life cycle assessment "studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition, throughout production, use, and disposal."[6] Basically it looks at the entire life of a production from creation ("cradle") to destruction and/or recycling ("grave"). The key focuses are on energy and material utilization. It is also seen that a Life Cycle Assessment (LCA) must also be evaluated on an individual basis. The environmental impacts differ based on the capabilities of a society for processing the materials and supplying the energy required to manufacture, run, and process the end of life product.

When one is conducting an LCA of a product, several questions must be asked: What are the capabilities of the society in which this product is to be used?, What is the availability of the required materials, and what is the cost associated with processing and transporting them?, How much energy is required to construct, transport, operate, and dismantle/recycle the product?, How much raw material is to be used in the operation stage of the life of the product?, At the end of product's "life," what will happen to it? Will it be trashed and left in a landfill? Will it be left to naturally decompose? Or will it be used as fuel for subsequent processes?[7] In some societies it may be more cost effective or environmentally sound to dispose of an item rather than attempting to recycle it.

It is these concepts that have resulted in the keying of a term known as "eco-efficiency." Eco-efficiency is a term used to quantify the ratio of economical impact to that of environmental impact.[8] It is therefore used as a method of "quantifying the sustainability of products and processes."[8]

The increase in interest surrounding the LCA methodology has resulted in toolkits being developed to aid engineers in the design stage, such as the EIO-LCA toolkit from Carnegie Mellon.[9] Europe also has guidelines they have named the European Eco-Design Framework-Directive (2005/32/EC).[10] The point of this directive is address the environmental impacts resulting from the production, use, and end of life.

2.3. Exergy

The study of thermodynamics revolves around two main laws. The first law simply states that energy can neither be created nor destroyed, but only transferred. Therefore, it is often referred as the "conservation of energy." The second law assigns a quality to energy in the form of entropy. The quantifiable property of this quality is referred to as exergy, formally available energy. Exergy is used to relate the maximum possible work that could theoretically be extracted from a process or substance with respect to defined environment conditions. It enables engineers to "quantify the loss of the quality of the energy."[11] Since exergy represents a loss, the laws of conservation do not apply. These losses represent irreversibilites. This property makes it possible to highlight areas in need of improvement within a system; however, it does not provide a guideline about how to accomplish this. It is rather easy to see how these values relate to sustainability.

Table 1: Energy vs. Exergy (Szargut et al.)

	Energy	Exergy
1	is subject to the law of conservation	is exempt from the law of conservation
2	is a function of the state of the matter under consideration	is a function of the state of the matter under consideration and of the matter in the environment
3	may be calculated on the basis of any assumed state of reference	the state of reference is imposed by the environment, which may vary
4	increases with rise of temperature	for isobaric processes reaches a minimum at the temperature of the environment; at lower temperatures it increases as the temperature drops
5	in the case of the ideal gas, does not depend on the pressure	always depends on the pressure
6	for an ideal vacuum equals zero	for an ideal vacuum is positive

The total exergy of a substance is broken down into three main parts: thermal, kinetic, and potential; where the thermal portion is composed of both physical and chemical exergies. Controlled electrical energy is considered to be all exergy because it is theoretically completely convertible to useful work.

$$B = B_k + B_p + B_{th}$$

$$B_{th} = B_{ph} + B_{ch}$$

The exergetic efficiency, or second law effectiveness, is expressed similarly to that of energy efficiency as being the output divided by the input.

$$\eta_B = \frac{\sum B_{output}}{\sum B_{input}}$$

It is easy to see with diminishing resources, that systems must be developed to more effectively use the available energy. Typically, with an increase in energy efficiency, and increase in effectiveness is also achieved since less energy is typically lost in emissions and through internal consumption.[12]

When developing sustainable methods, it is important to also incorporate energy loss and the loss of the quality of that energy. In some instances the exergy is a more useful property than the energy because it shows the amount of energy that is useful, and can be used to possibly drive subsequent processes. "This observation applies equally on the component level, the process level, and the life cycle level."[12] So it is clear to see how exergy represents a promising tool in sustainable design.

An exergy analysis done on a domestic-scale solar water heater showed that the process is not very exergetic efficient because of the low quality of the energy of the exiting water. The author of that study concluded that the highest loss of exergy occurred in the storage of the water.[13]

Within the scope of thesis, exergy will be considered on a single component/process basis; however, there are mass applications that will now be discussed.

2.3.1. Global Application of Exergy

Several studies have been conducted on a mass residential-commercial demographic using exergy in their evaluation of the energy use. The first study to be addressed is a projected study in the Turkish "residential-commercial" sector over a period of time from the years 2000 to 2020. The study looks at the effect of heat generation and loss, conversion of fossil fuels to hydrocarbons, work utilization and production, and kinetic productions due to moving matter. Data was collected from various sources regarding the current population in 2000, resulting in values of energy efficiency ranging from 55.60% to 65.54% from 2000 to 2020 respectively, while at the same time reporting exergetic efficiencies ranging only from 8.02% to 10.07%.[14] The study investigated many aspects of the residential sector with emphasis on heating, both water and space, cooking and various other heat generating processes. Basically the authors looked at the areas with the highest areas of exergy loss. It is possible to see that even by increasing the energy efficiency of a society by 10% can still yield a very low increase in exergetic efficiency, only around 2%.

A project entitled the Annex 49 has taken a stride toward what they call a "Low Exergy" (LowEx) approach. This method seeks to use the low quality "waste heat" which is usually considered a complete exergy loss in normal systems.[15] For the most part, what they are trying to do is match the demand with the appropriate supply, instead of always supplying "high quality" energy.

In 2007, a paper was published by A. Hepbasli et al. analyzing the energy and resource use within the Turkish residential-commercial sector.[16] The study addressed items that create a significant amount of heat within an establishment. They then looked at the energy vs. exergy efficiencies associated with these processes with respect to the energy or exergy of the fuel source. The objective of the paper was to highlight key areas that needed improvement.

These studies provide a mass picture of where energy is being used on the product level, but they are unable to give insight into what causes the losses. When it comes to creating metrics for design, it is necessary to know the exact cause of the exergy loss. This is important because isolation allows for added consideration. This study does not aim at identifying all of the losses, but it does provide a means for quantifying them.

2.4. Current Exergy Models

The idea of drawing comparisons between engineering concepts and biological systems is not a new one. Engineers have been turning to nature for a long time for inspiration in design. A recent publication relates information processing of computer-based technologies with the information processing of biological systems.[17] The comparison is made on a basis of information performance, measured in MIPS, to the exergy consumption, in Watts. This data is collected from various computer systems and is then compared to the brain processing of various organisms. It is concluded later on in the discussion of the paper that the processing power of mammalian brains is around 107 MIPS/W, where the fastest current CPU's only operate around 100 MIPS/W. The author continues on to compare the theoretical amount of energy that would be required to produce a processor with the same efficiency of a brain. At current rates of increasing processor efficiencies, the theoretical processor would require 100 times less energy than if the processing power increased proportionally with exergy demand. Because the author used a Carnot approach to evaluate exergy, their method is not applicable to this study.

2.4.1. Cellular Biology

Current methods of exergy calculation within living cells are poorly developed. The interactions at intracellular conditions are often overlooked, leading to a lack of acceptable second-law methodologies.

The cell is considered a stable, yet highly dynamic system where material and energy flows are constantly happening and changing based on demand. Even with these constant interactions the cell is able to maintain a fairly consistent range of conditions, known as homeostasis.

Current thermodynamic methods well suited for typical systematic processes are not adequate for analyzing processes within living cells. The standard input-output approach can be applied to the cell as a whole; however, when it comes to investigating individual biochemical processes found within a cell, such as ATP synthesis, the intracellular conditions and interactions have to be considered. At the cellular level, the effects of inertial and gravitational forces are greatly reduced and can be neglected in the calculation. It is also safe to assume that changes in pressure and temperature are very small due to the homeostatic characteristic of the cell. This leaves just the effects of chemical interactions for the exergy calculation. Overall the quality of the exergy calculation will rely on the incorporation of as many intracellular interactions as possible. With the inability to understand the entire scope of every intracellular interaction, the best that can be done is incorporating as many interactions as are currently known.

In recent years there has been an increasing utilization of exergy within the biological/cellular world. A group at the Delft University of Technology in the Netherlands has published two papers within the past five years relating the concepts of exergy and the second law to processes within cells. The initial publication entitled, "Thermodynamic analysis of the living cell: design of an exergy-based method," the authors investigate the key aspects within the intracellular space that would contribute to an exergy based calculation.[18] To demonstrate their procedure, an exergy calculation was conducted for the energy carrying compound known as ATP, or adenosine triphosphate. With this calculation they were able to demonstrate that previous measures of available energy quantification, such as Gibbs free energy, were inadequate and that the ATP compound actually had around twice the potential to do work than previously thought. The following is a synopsis of the exergy formulation constructed by Lems et al.

Gibbs free energy data is readily available for most biochemical compounds and can be used to calculate the exergy of a biochemical compound using the following equation.

$$Ex_A^{0'} = \sum_i v_i Ex_{element,i}^{0} + \Delta_f G_A^{0'}$$

The first term on the right side of the equation contains the stoichiometric number, *v*, and exergy at chemical standard conditions of an element within the compound A. This is a start, but it is not sufficient for modeling the conditions found within a cell, since the cell is seldom at or even close to biochemical standard conditions. The authors then go on to introduce several effects to the exergy that can be accurately quantified; these include: effects of dilution, acid and basic dissociation, ion-complex formation, ionic interactions, non-ionic interactions, and electrical potential. Considering these interactions, results in a new equation for the exergy of ATP:

$$Ex_{ATP}^{\theta} = Ex_{elements}^{0} + \Delta_f G_{H_4ATP}^{0'} + \Delta Ex_{conc} + \Delta Ex_{acid} + \Delta Ex_{magnesium} + \Delta Ex_{ionic}$$

ATP is the chief molecule in transporting energy within the cell. It is made of three phosphate groups attached to a ribose and adenine group. Since the triphosphate group is the only portion of the molecule that is responsible for transferring energy, it is the only part of the molecule that will be considered for the exergy analysis. Because of this the exergy of the elements is evaluated based on the equation:

$$3\mathrm{P}(s) + 4\frac{1}{2}O_2(g) + 2\mathrm{H}_2(g) \rightarrow P_3O_9H_4$$

Standard conditions are taken to be 101.3 kPa and 298.15 K. This yields an exergy of the elements to be:

$$Ex^0_{elements} = \sum_i v_i Ex^0_{element,i} = 3 \cdot Ex^0_P + 4\frac{1}{2} \cdot Ex^0_{O_2} + 2 \cdot Ex^0_{H_2} = 3074.3\, kJ/mol$$

Similar calculations are done for the effect of Gibbs energy of formation, compound dillution, acid dissociation, magnesium-ion binding, and ionic interactions yielding an exergy of ATP of 299 kJ/mol. In order to see how much useful energy is contained within each mole of ATP, the exergy calculated for ATP needs to be combined with the exergy of the products of the hydrolysis reaction. The hydrolysis reaction is how the cell releases the energy stored within the ATP molecule.

$$ATP + H_2O \rightarrow ADP + P$$

After subtracting the exergies of ADP, water, and inorganic phosphate from the 299 kJ/mol calculated for ATP, the authors found that the reaction yielded 57 kJ/mol of useful work. This differs from the previously accepted value of -30.5 kJ/mol as given by the Gibbs free energy of the reaction. The negative sign denotes a favorable reaction. This data shows that the Gibbs free energy is not an acceptable substitute for exergy, since many other local environmental factors within the cell affect the amount of useful energy that is available to the surrounding systems. It is only a valid at biochemical standard conditions, a state that cells are rarely at.

In a more recent publication, the same group, S. Lems et al. (2009), investigated glucose and fatty-acid breakdown within the cell based on the exergy analysis previously described.[19] This study, like the previous one are based off of material from Szargut et al., with the exception of liquid water being taken as the lowest state of hydrogen, instead of water vapor. This assumption more adequately relates to biochemical conditions, establishing the exergy of water at standard temperature and pressure to be zero.

In the first stage of glucose breakdown, glycolysis, one molecule of glucose is transformed into two molecules of pyruvic acid, two molecules of ATP, and 2 molecules of NADH.

$$C_6H_{12}O_6 + 2\mathrm{P} \rightarrow 2\mathrm{C}_3H_4O_3 + 4\mathrm{H}_{NADH} + 2\mathrm{P}_{ATP}$$

For consistent analysis, the authors took the exergy of the inorganic phosphate (P) to be zero and the exergy of the phosphate groups of ATP (P_{ATP}) to be 57kJ/mol, as previously stated. With that stated, it can be seen in the following table, that 79% of the exergy available in glucose is transferred to pyruvic acid, 14% to the activated proton-electron pairs within NADH, and 3.8% to the activated phosphate groups of ATP. This shows that only 100kJ or 3.4% of the exergy is loss in this conversion process.

Table 2: Glycolysis (Lems et al., 2009)

Exergy input		*Exergy output*	
1 Glucose	2955 kJ	2 Pyruvic acid	2336 kJ
2 P	0 kJ	4 H_{NADH}	405 kJ
		2 P_{ATP}	114 kJ
Total input	*2955 kJ*	*Total output*	*2855 kJ*
		Exergy loss	*100 kJ*

The next stage takes the pyruvic acid left over from glycolysis and degrades it to carbon dioxide and water in the mitochondria.

$$2C_3H_4O_3 + 6H_2O + 2P \rightarrow 6CO_2 + 16H_{NADH} + 4H_{FADH_2} + 2P_{ATP}$$

The following table shows the exergy distribution of pyruvic acid into the proton-electron pairs of NADH, $FADH_2$, ATP, and CO_2. CO_2 is taken to have little to no meaningful exergy since CO_2 is the reference-state for carbon. 9% of the exergy contained within the pyruvic acid is lost during this phase.

Table 3: Pyruvic Acid Degredation (Lems et al., 2009)

Exergy input		*Exergy output*	
2 Pyruvic acid	2336 kJ	16 H_{NADH}	1719 kJ
6 H_2O	0 kJ	4 H_{FADH2}	293 kJ
		2 P_{ATP}	114 kJ
		6 CO_2	~0 kJ
Total input	*2336 kJ*	*Total output*	*2126 kJ*
		Exergy loss	*210 kJ*

The NADH and $FADH_2$ from this stage are then oxidized to create the useful energy that will be used to create a large number of ATP in the electron transport chain. Basically, the oxidation relocates protons from the mitochondrial matrix to the cytosol. This process creates a larger concentration of protons outside of the mitochondria, which can then be used to drive the ATPase, the molecular motor that assembles ATP molecules.

$$16H_{NADH} + 8\mathrm{H}_{FADH_2} + 6\mathrm{O}_2 + 104\mathrm{H}^+_m \rightarrow 12H_2O + 104\mathrm{H}^+_{cytosol}$$

The following table shows the oxidation reaction that results in the energy to be used in the following step, the proton gradient ($104H^+$ (PMF)). PMF is short for Proton Motive Force, the primary source of energy to drive the ATPase motor. 121 kJ or 5% of the exergy contained within the NADH and FADH molecules is lost.

Table 4: Oxidation of NADH and $FADH_2$ (Lems et al., 2009)

Exergy input		*Exergy output*	
16 H_{NADH}	1719 kJ	104 H^+ (PMF)	2184 kJ
4 H_{FADH2}	293 kJ	12 H_2O	0 kJ
4 H_{FADH2}	293 kJ		
6 O_2	~0 kJ		
Total input	*2305 kJ*	*Total output*	*2184 kJ*
		Exergy loss	*121 kJ*

The final process involved in glucose breakdown to ATP uses the proton gradient created in the previous process to drive the ATPase engine and convert inorganic phophate into the useful triphophate molecule.

$$104\mathrm{H}^+_{cytosol} + 26\mathrm{P} \rightarrow 104\mathrm{H}^+_m + 26\mathrm{P}_{ATP}$$

It can then be seen in the following table that a total of 705 kJ, 32%, of exergy is lost in this process.

Table 5: ATP Synthesis (Lems et al., 2009)

Exergy input		*Exergy output*	
104 H^+ (PMF)	2184 kJ	26 P_{ATP} (cytosol)	1479 kJ
26 P (cytosol)	0 kJ		
Total input	*2184 kJ*	*Total output*	*1479 kJ*
		Exergy loss	*705 kJ*

The ATPase engine is considered reversible, so the loss observed in this process is considered to be due to the transport of the protons across the membrane.[19]

With this information in hand, the overall breakdown of glucose can be summarized.

$$C_6H_{12}O_6 + 6O_2 + 30P \rightarrow 6CO_2 + 6H_2O + 30P_{ATP}$$

An exergy balance of this process can be done by combining the information from the internal processes. This is shown in the following table. It can be seen that of the 2955 KJ of available energy within glucose, 1707 kJ is converted into useful energy within the cell. The remaining 1248 kJ is considered to be a loss. This results in an exergetic efficiency of 58% for the breakdown of glucose.

Table 6: Overall Breakdown of Glucose into ATP (Lems et al., 2009)

Exergy input		*Exergy output*	
1 Glucose	2955 kJ	30 P_{ATP}	1707 kJ
6 O_2	~0 kJ	6 H_2O	0 kJ
30 P	0 kJ	6 CO_2	~0 kJ
Total input	*2955 kJ*	*Total output*	*1707 kJ*
		Exergy loss	*1248 kJ*

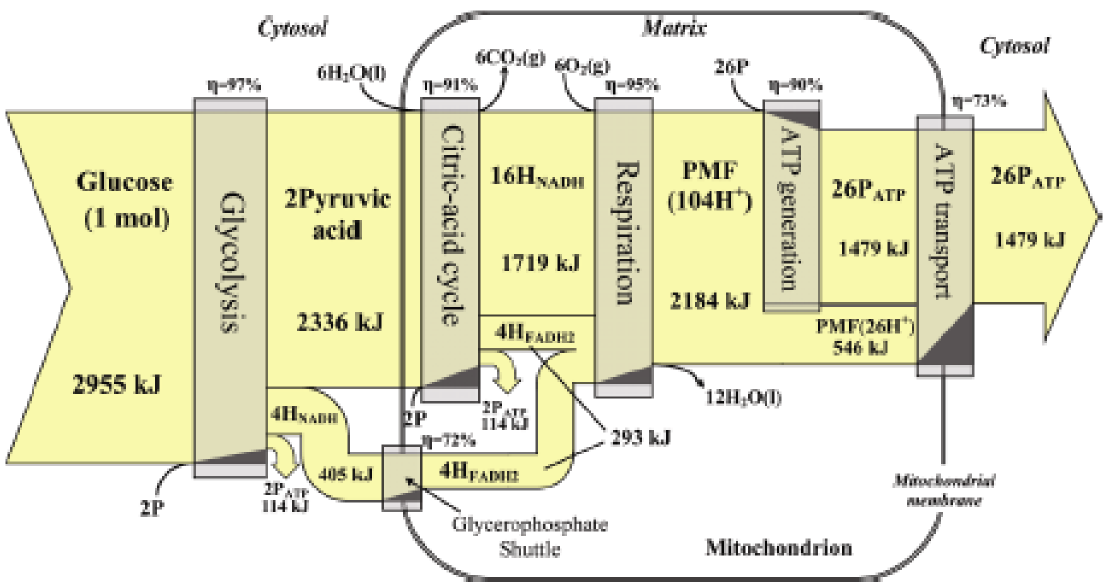

Figure 1: Exergy Flow Diagram of Glucose Breakdown into ATP (Lems et al., 2009)

Figure 1 is referred to as an exergy flow diagram, and is a commonly used means of visually representing exergy.

The authors also perform an exergy analysis on the breakdown of palmitic acid; however, that analysis will not be fully covered. The overall reaction and breakdown of palmitic acid to CO_2, H_2O, and ATP results in an exergetic efficiency of 60%. The reaction equation, exergy balance, and exergy flow diagram are as follows.

$$C_{16}H_{32}O_2 + 23O_2 + 106\mathrm{P} \rightarrow 16CO_2 + 16H_2O + 106\mathrm{P}_{ATP}$$

Table 7: Overall Breakdown of Palmitic Acid (Lems et al., 2009)

Exergy input		*Exergy output*	
1 Palmitic acid	9994 kJ	106 P_{ATP}	6030 kJ
23 O_2	~0 kJ	16 H_2O	0 kJ
106 P	0 kJ	16 CO_2	~0 kJ
Total input	*9994 kJ*	*Total output*	*6030 kJ*
		Exergy loss	*3964 kJ*

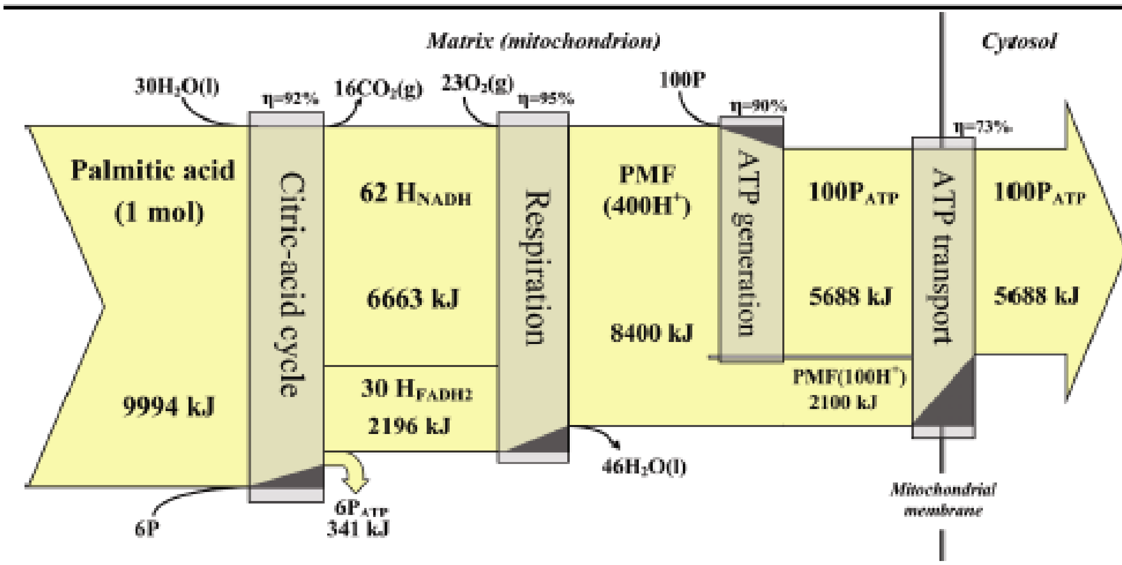

Figure 2: Overall Breakdown of Palmitic Acid (Lems et al., 2009)

It is important to note that these values are calculated at assumed, generalized conditions. Depending upon the intracellular conditions losses could be either higher or lower. It is currently not possible to account for all of the interactions within a cell.

2.4.2. Dishwasher

The dishwasher was chosen because of its excessive use of energy and water. In the past few years dishwashers have been developed to use less of these two resources, but there is still room for improvement. The dishwasher used in this study is a GE

Nautilus with power scrub wash system and quiet power sound package, model number GSD3230F01WW. It is composed of a plastic shell/case and a timer controlled system. The system is also equipped with an array of buttons for choosing options like “pot scrubber,” “hi-temp wash,” and “heated dry.”

Throughout the research process of this thesis, very little information was encountered directly relating an appropriate exergy analysis to the dishwashing process. The only actual analysis found is an incomplete one in that it is only looks at exergy in a strict heat transfer process from the fluid to the surrounding environment. In order to calculate the effectiveness of a dishwasher, the author simply divides the Carnot factors associated with the needed heat, with that of the supplied heat.[20]

$$\eta_{EX} = \frac{EX_{out}}{EX_{in}} = \frac{1 - \frac{T_{ref}}{T_{need}}}{1 - \frac{T_{need}}{T_{supply}}}$$

This method does not take into account losses associated with the transport and heating of the water, two factors that must be addressed.

2.4.3. ENERGY STAR

One design metric that currently exists governing the operation of dishwashers is the ENERGY STAR criteria. ENERGY STAR currently has a set of standards for both the energy and water use of dishwashers that are higher than the federal standards. It states that for a “standard sized” dishwasher (greater than eight place settings and six serving pieces) in order to warrant the ENERGY STAR approval it must be rated to use less than 324 kWh of electricity per year and less than 5.8 gallons of water per cycle. Additionally for a “compact sized” dishwasher (less than eight place settings and six serving pieces), less than 234 kWh/year and less than 4 gallons per cycle is allowed. The current federal standards say that the standard dishwasher must use less than 355 kWh/year and 6.5 gallons/cycle, and the compact dishwasher must use less than260 kWh/year and 4.5 gallons. ENERGY STAR recently (2009) raised their standards up to the aforementioned limits and plans to raise them again in 2011 to: standard 307 kWh/year and 5.0 gallons per cycle; compact 222 kWh/year and 3.5 gallons/cycle.

The previous metric was based on a quantity known as the “energy factor” (EF). It is expressed in cycles per kWh and is defined as follows, where M is the sum of the machine electrical energy per cycle and W is the water heating energy consumption per cycle. As can be seen, the previously used metric only set a standard for the energy consumption.

$$EF = \frac{1}{M + W}$$

2.4.4. Thermodynamic Efficiency and Effectiveness and Sustainable Engineering Design Metrics

While the thermodynamic behavior of the cellular system and the mechanical system are founded on first and second law principles, the models and methods described in the previous sections have focused on different aspects to describe the system performance. It is necessary that direct comparisons of the resource use for these two systems be analyzed using both the exergy method and the LCA tool in order to establish common attributes that can serve to identify design metrics. Extensive thermodynamic modeling of specific functions of each system is necessary to establish both the performance and the sustainability aspects of each.

CHAPTER 3: EXPERIMENTAL SETUP

The focus of this chapter is to present the setup for the thermodynamic model of the dishwasher. The overall setup will be discussed and the appropriate equations will be presented.

3.1. Exergy Relations

The exergy relations provided hereafter are derived from several sources, such as textbooks and other publications; however, to maintain consistency, the relations for closed systems provided by Szargut et al. [11] will be presented. The sign convention used assumes that all inputs result in a positive value; consequently, all outputs from the system are represented by a negative value.

3.1.1. Assumptions

Before any calculations can be conducted, a few assumptions will need to be made regarding the system. The first consideration to be evaluated is the boundary and whether the system will be represented as closed or open. At first glance, it would be easy to assume that the dishwasher would represent an open system, with water able to freely flow across the boundary. On the other hand, since the system neither expels nor receives any water during the actual "wash" cycle, the system is taken to be a closed control mass. Another key assumption is to how the boundary handles heat loss. As previously stated, thermocouples 7 and 8 are used to measure the heat transfer through the case. These temperatures are taken to represent the entire case. The exposed surface area of the case is also needed, but because of the complex geometry, an estimate is taken. For calculation of the heat transfer rate, defined by Fourier's Law:

$$Q = -kA\frac{dT}{dx} = -kA\frac{T_2 - T_1}{t}$$

The thermal conductivity of the case is taken to be that of ABS plastic. This material assumption is made because actual data is unknown. The front door is made of a metal; however, it is not to be considered because it contains insulation. The bottom of the case is also considered to be adiabatic because of the inability to properly measure the temperature gradient across it.

The last assumption concerns the state of the water within the system. It was observed through measurement during the wash cycle, that several hundred grams of water are somehow lost. Since the system is closed to the surroundings, the only explanation is that the water enters the 2-phase region, and there is liquid water and water vapor together, a quality exists and is defined:

$$x = \frac{massofvapor}{totalmass}$$

Since it is the entire wash cycle that is being looked at, the two important points to address are the beginning and ending conditions of the cycle. This includes the total power used during the cycle, the mass of water throughout the cycle, and beginning and ending temperatures of the appropriate thermocouples. Also since the mass of water in the basin is at the same elevation and velocity as when the cycle started, changes in kinetic and potential energies are equal to zero. The quality of electricity is considered to be all useful; therefore, the energy contained within the electricity is taken to be the exergy as well.

3.1.2. Equations of Exergy

In order to evaluate the change in exergy of the water throughout the cycle, properties need to be evaluated for the water at the begining and end of the cycle. These properties include the internal energies and entropies at the two points; both are available from many different printed and electronic sources. The following equation shows the exergy content of the water at a particular state.

$$\Phi_1 = m(u_1 - u_0) - mT_0(s_1 - s_0)[kJ]$$

If state one is the start of the cycle and state two is the end, then the resulting properties and exergy at state two are shown by:

$$u_2 = u_f + xu_{fg}$$
$$u_{fg} = u_g - u_f$$
$$\Phi_2 = m(u_2 - u_0) - mT_0(s_2 - s_0)$$

The same mass is used in both states because the overall mass of the system does not change, control mass. So, in order to see the change in available energy during the "wash" cycle the equations are combined resulting in the following:

$$\Delta\Phi_{water} = m(u_2 - u_1) - mT_0(s_2 - s_1)$$

This value is of great importance, since it shows the amount of energy effectively transferred from the electricity to the working fluid. Another way of quantifying how well a system transfers energy is by evaluating its effectiveness or "second-law efficiency." The effectiveness is evaluated similarly to the way energy efficiency is. It is a ratio of the output over the input. In the case of the "wash cycle" the output is the change in availability of the water and the input is the provided electricity to the coil and pump.

$$\varepsilon = \frac{exergy\ of\ useful\ products}{exergy\ supply} = \frac{\Delta\Phi_{water}}{w_{in}}$$

One way that an exergy analysis can highlight key losses within a system, is by looking at irreversibilities, or exergy losses. Irreversibilities are unavoidable losses associated with the transfer of energy. The exergy loss due to irreversibilities is represented by:

$$I = T_0\sigma$$

Sigma represents the entropy generation due to the process.

The following equation demonstrates irreversibilites caused by heat transfer.

$$I_{HT} = T_0 Q\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

In addition, the irreversibility within a pump is expressed by:

$$I_p = v_m(p_e - p_b)\left[\frac{1}{\eta_i}\left(\frac{1}{\eta_m} - 1\right) + \frac{T_0}{T_m}\left(\frac{1}{\eta_i} - 1\right)\right]$$

Because of unknown conditions and constraints within the system, this irreversibility will not be evaluated. Properties regarding the pump, such as outlet pressure, and efficiencies (both mechanical and fluid compression) cannot be addressed without destroying the testing equipment.

3.2. Apparatus Setup

The dishwasher is placed within a safety basin. This is done to ensure that any leakage is captured, preventing damage to the laboratory space. This basin-dishwasher combination is then place atop a digital scale. The scale servers as a means to measure the amount of water contained within the system at any point during the operation.

Electrical and water connections are then made. A custom emergency kill switch has been wired in-line with the power cord before it is plugged into the Watts Up power meter. The meter is connected to the wall socket. The water inlet hose is connected using two segments of garden hose with an in-line volumetric flow meter connecting the two hoses. This flow meter is a fail-safe for the scale. It also serves as a means to ensure that no water enters the system randomly. The hose is then connected to a hot water source through the use of a custom adapter. The outlet hose is simply inserted into a five-gallon bucket. Because the dishwasher uses more than five gallons of water throughout its operation, this bucket will have to be emptied several times.

In order to track the thermodynamic state of the dishwasher during operation, a series of eight thermocouples were attached to the system at various points.

1. Coil
2. Bottom basin
3. Inlet
4. Exhaust
5. Lower drawer
6. Upper drawer
7. Inner wall at top of case
8. Outer wall at top of case

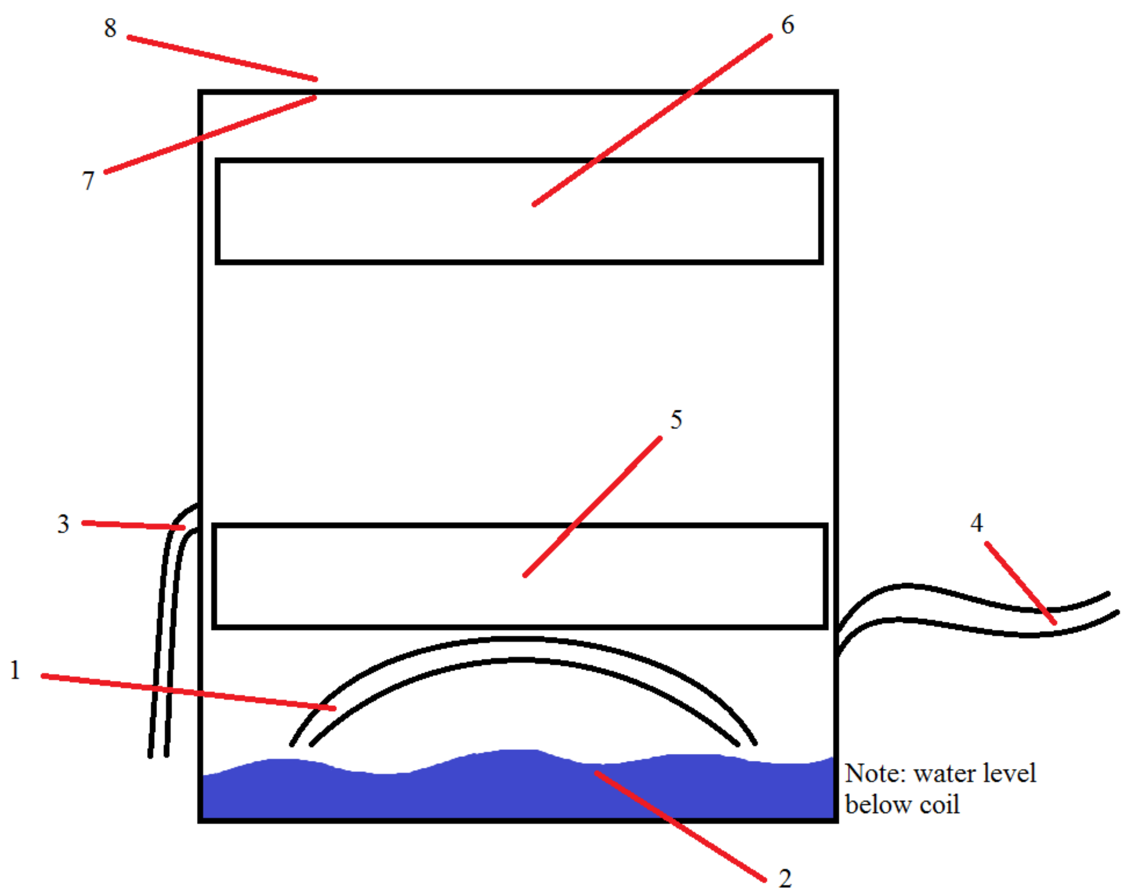

Figure 3: Dishwasher Thermocouple Locations

Type T thermocouples were used because of their low full scale range, -200 to 350 °C. The coil at its hottest point reaches around 340 to 350 °C. In order to acquire the data from these thermocouples, an NI BNC-2120 DAQ board was utilized in conjunction with LabView. Because of this setup, a cold junction compensation, CJC, was able to be set manually for the thermocouples.

The basin location serves as a means of representing the bulk working fluid condition, where the locations 1, 7, and 8 are key points of thermodynamic losses. 7 and 8 are the inner and outer surface temperatures of the "thin-wall" medium where heat transfer occurs and is lost to the environment. The coil temperature is measured because losses occur whenever energy is transferred, and in the case of the coil, a massive amount of energy is converted from an electrical potential to heat. The number 5 and 6 thermocouples on the two drawers serve strictly as a means to observe the temperature distribution within the case, ensuring that the system's enclosure can be modeled as a lump control mass. They will also serve as the reference temperature for the analysis of the coil heating process.

The dishwasher has several settings available for the user to select from, depending on the input and the user's preference. On the front panel, there are toggle buttons that allow for the system to operate for a larger than normal load, increased wash temperature, and heat-assisted drying. For the purpose of this experiment, the two extremes will be tested to provide an overall range of operation.

There are also many different segments which make up the full run-time of the dishwasher. They begin with a heated pre-soak, followed by a pre-wash; before being washed rinsed and dried. Since the underlying usage of a dishwasher is to clean or wash dishes, the longest "wash" cycle was used. During this cycle, the dishwasher neither drains nor fills, and the motor and heating coil run at a consistent rate.

Measurements of temperature and power were taken at two-second intervals, and the mass and water meter was monitored at a five-minute increment. The two seconds was chosen based on a spreadsheet provided with the power meter for measuring a process of around 120 minutes. This interval was also applied to the thermocouple measurement in order to be able to easily pair the data of the two systems after the collection phase. The five-minute interval was more for convenience, but also because throughout the entire run, at only one point is there less than five minutes between draining events.

CHAPTER 4: EXPERIMENTAL RESULTS

The following results are presented from experimental data as introduced in the preceding sections. They are not meant to model every type/model of dishwasher, but to provide a rough estimation of the energy and water usage of a sample dishwasher. These calculations are based on the exergy equations stated in an earlier chapter. The properties used are taken from an online flash program.[21] Results from this calculator are consistent with other printed tables. The thermal conductivity for the walls of the dishwasher is assumed to be 0.17 W/m-K, that of ABS plastic. [22]

4.1. High Load Settings

The high load setting was used to gain a reference point for the maximum use of energy and water during the wash cycle. The dishwasher was allowed to run through its entire dial timer with settings of: pots and pans, hi-temperature wash, and heated dry. Temperatures were measured at the locations indicated in Figure 3 and the control mass was tracked.

Water content of the system during the "wash" cycle was seen to be fairly consistent through testings, only varying a few hundred grams. It was also noticed that during the cycle, a noticeable amount of mass, 0.1-0.2 kg was seen to be “lost.” The initial assumption was that there was a leak in the system; however, after further investigation, no leaks were observed. Further investigations indicated that the water within the dishwasher is able to go from a saturated liquid into its two-phase region during the washing sequence. It also important to point out that the temperature distribution within the system is fairly uniform, at least during the wash cycle, as indicated by the temperature profiles in the upper and lower trays.

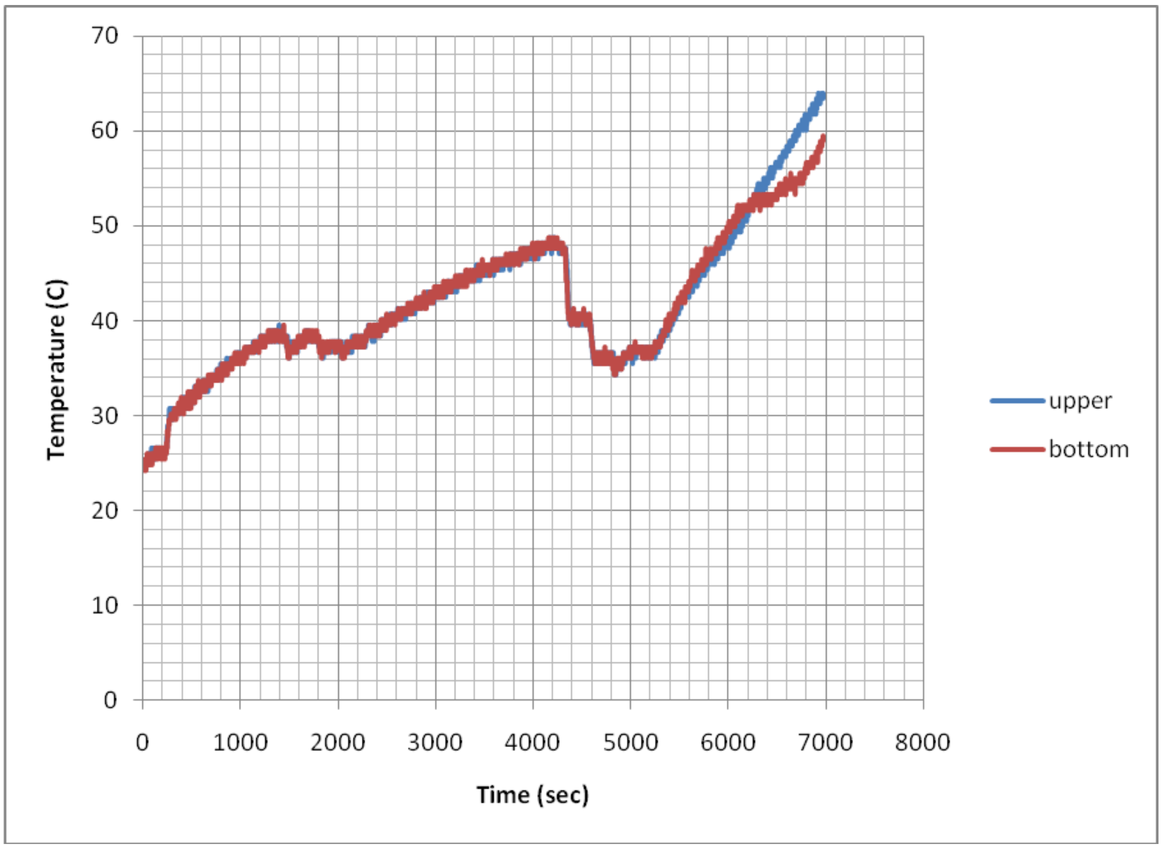

Figure 4: Upper Drawer vs. Lower Drawer (high setting)

The following is a graphical representation of the water use in kilograms.

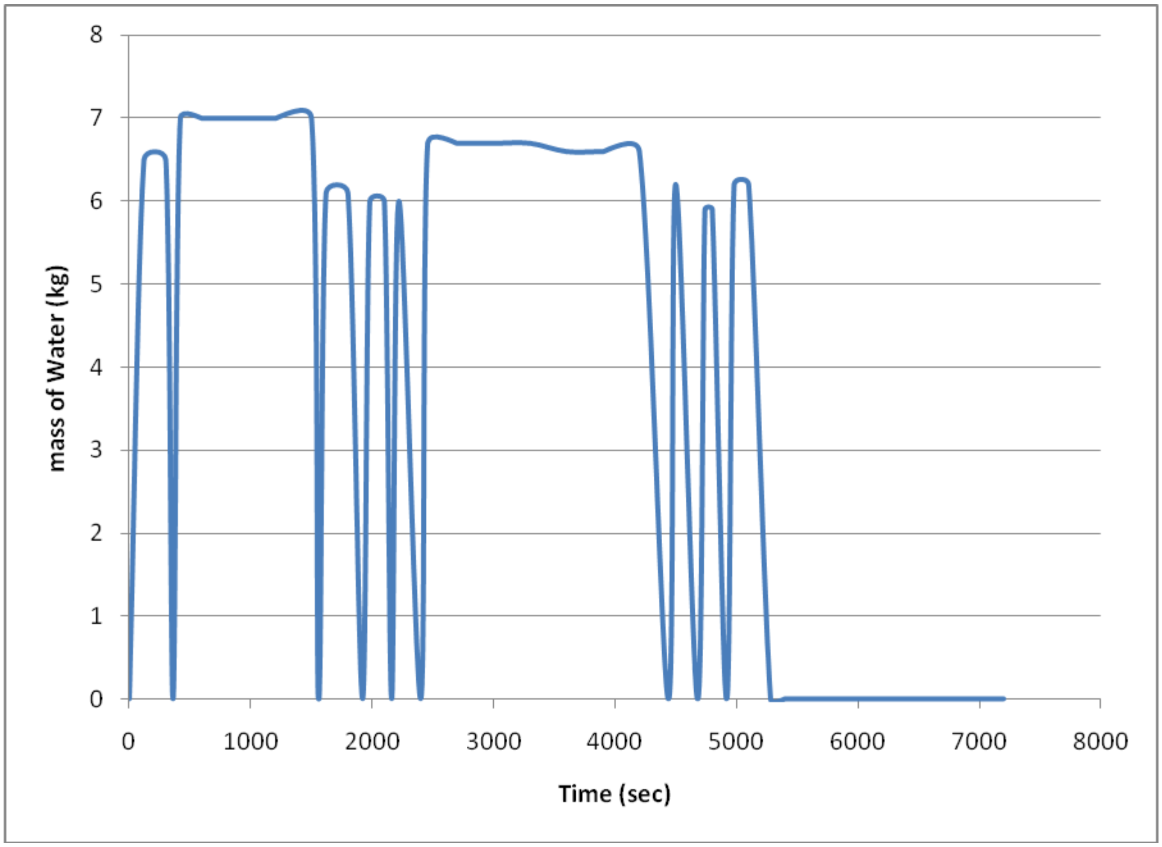

Figure 5: Water Consumption (high setting)

The system fills and drains nine times; however, during the "wash" cycle, the system fills and empties only once. This allows the analysis to be conducted as if the system were in an initial and final state. The initial state is taken at the point when all of the water has entered the system and the coil is energized, and the final concludes as the drain valve opens and the coil is shut off. It is the temperatures at these two points that is used in the exergy calculations.

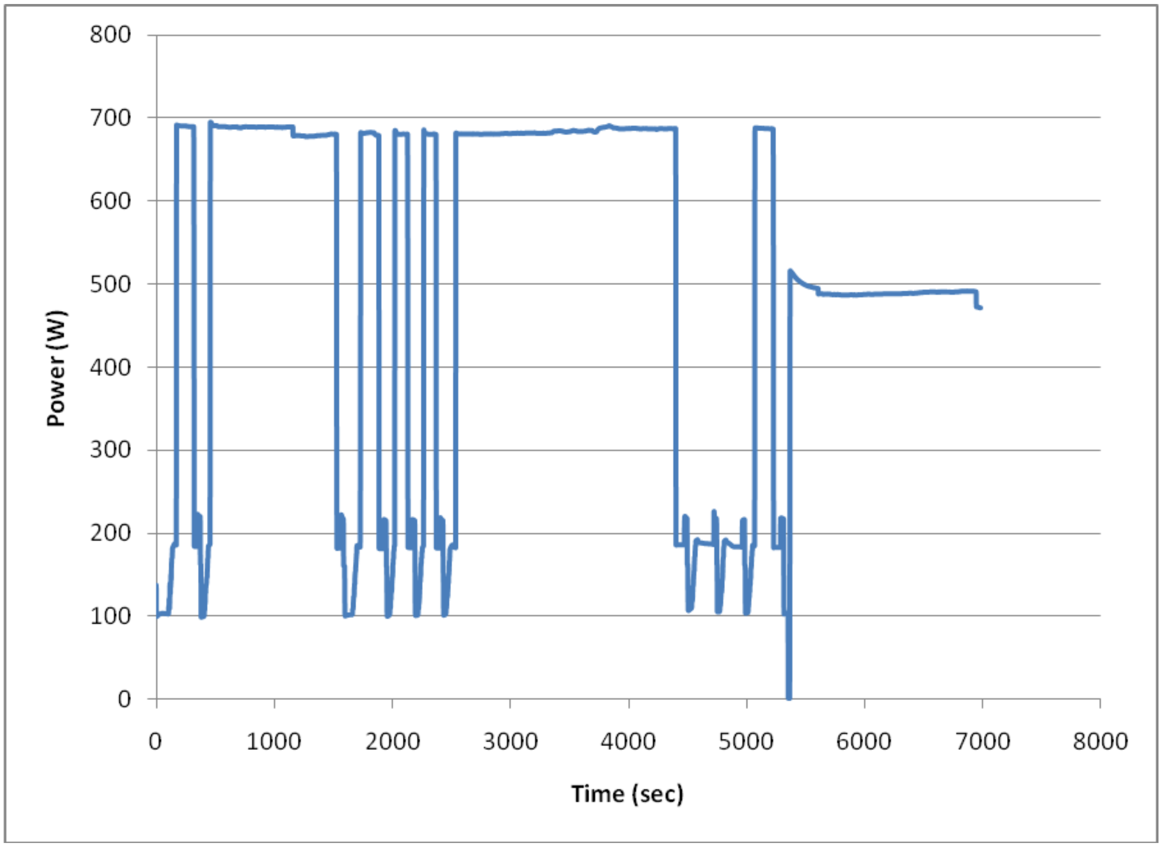

Figure 6: Power Usage (high setting)

Power has been monitored at a two-second interval using the Watts Up meter. It is clear that the highest power consumption occurs when the motor and coil are both energized. Throughout the majority of the cycle, with the exception of the drying process, the motor and coil are used in tandem. During the drying process, only the coil is consuming electricity. The part of this graph that is important for the model is the center longer portion, representative of the wash cycle. The cycle lasts approximately thirty five minutes. With that in mind the total work applied to the system can be calculated from the area under that portion of the curve. More simply put, the power multiplied with the running time gives the total energy transferred during that portion of the wash.

Table 8: Properties and Preliminary Calculations (high setting)

	State 1	State 2	
m	6.7	6.7	kg
x	0	0.014925	
T	39.01	47.097	C
u	163.308	230.5777	kj/kg
s	0.5589	0.7772	kj/kg-k
To	24.5	24.5	C

Input E	1298.939	kJ
change in ex	15.5812	kJ
eff	0.011995328	
	1.20%	

After applying the appropriate equation, the result for the change in exergy or availability of the water during the wash cycle comes to 15.58 kJ. This number means that the work potential of the water has been increased by 15.58 kJ; however, for this to take place, 1298.94 kJ of electrical work must be applied to the system. Energy is transferred to the working fluid using both heating and imparting motion. The change in exergy captures how effectively this is done. Since the effectiveness is crudely defined as what is achieved over what is sacrificed, an effectiveness of 1.20% is achieved. The discussion will present the significance of the effectiveness, and show how it can be used for improving design.

With it being shown that such a small amount of exergy is effectively transferred to the working fluid, it is a reasonable assumption that since the cycle is dynamic and not at a steady state the water actually does accept a higher percentage of the supplied power. However, this exergy is then transferred from the water to the surroundings or internal components. This transfer is through both direct heat transfer, and transfer by impact and other kinetic effects of the water spraying within the system, transferring energy to the case and internal racks. In order to determine the energy associated with imparting motion, a first-law analysis was conducted to show that 631. 32 kJ of energy is unaccounted for in the calculations. This may be a significant part of the cycle, as it may be directly attributed to the function of the dishwasher in the form of moving water. It was unaccounted for because in order to measure the parameters needed the system would need to be dismantled, on operation that could have been destructive. In order to know information about the pump, pressures need to be measured at both the inlet and outlet of it. The inlet is simple enough, resulting from a gravitational potential of the water lying at the bottom of the system; however, there was not any nondestructive way to measure the pressure coming out of the pump.

Irreversibilities occur whenever energy is transferred. They represent a loss of potential for that transferred energy to do useful work. The irreversibilities associated with various heat transfer events within the system can be seen in the following table.

Table 9: Irreversibilites (high setting)

Exergy of Electricity	1298.939 kJ
Exergy Change of Water	15.5812 kJ
Irreversibility of Coil	25.9366 kJ
Irreversibility of Heat Transfer	1.145 kJ
Unavoidable Irreversibility Associated with Heating Water	640.4 kJ
Exergy Unaccounted For	615.8762 kJ

The following shows how as the wash cycle progresses and as water is heated, the irreversibility is decreased. This is due to the difference in temperature between the coil and water being reduced.

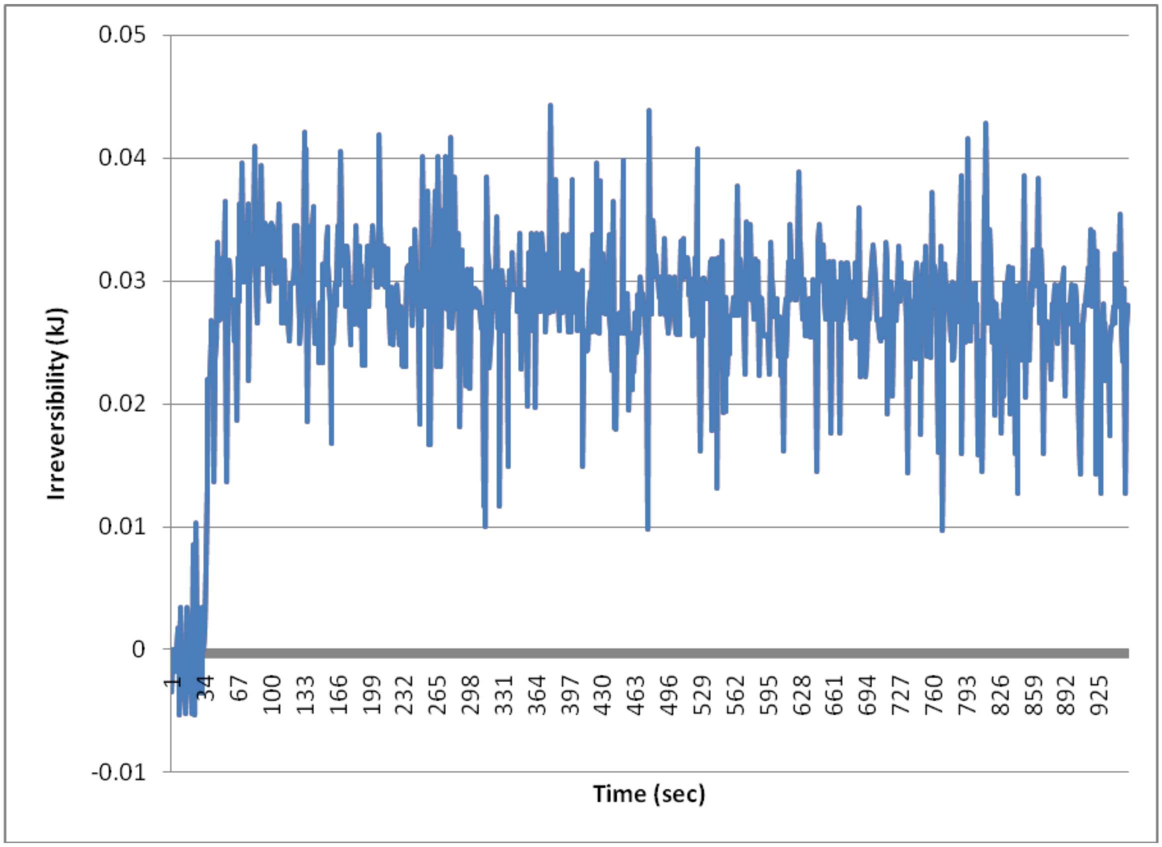

Figure 7: Irreversibility of Coil Heating (high setting)

When looking at the loss associated with simply raising the temperature of the system, with the same heat loss to the surroundings, 640.40 kJ is lost. This is an unavoidable loss resulting from the change of state of the water and heat transfer. It provides that the maximum effectiveness that can be achieved through the change of state of the water is 50.7% with 1298.939 kJ of electricity supplied.

The heating from the coil contributed a large part to the overall measured irreversibility of the process. 25.94 kJ of exergy is lost in the process of heating the water during the wash cycle. After the water is heated an additional 1.15 kJ is lost due to the effects of conduction. These two irreversibilities, along with the irreversibility of the water changing state make up the gross loss of availability within the system, totaling 667.48 kJ. This means that there is 615.88 kJ of exergy that is unaccounted for. This can be attributed to the loss caused by the water molecules impacting the internals of the dishwasher, imparting motion to the water, and losses within the motor and pump assembly.

By summing the irreversibilites and taking into account that the exergy transferred to and carried away by the water, it is possible to see the effect of other interactions on the system that either were not or could not be measured such as the pump performance and kinetic losses due to impacts within the system. During the washing cycle, 615.88 kJ of exergy from the electrical input is unaccounted for.

4.2. Low Load Settings

These settings consisted of a full dial timer; however, the optional settings were set to a normal cycle, hi-temperature wash off, and heated dry off. The experimentation was conducted in the same way as in the high load configuration and the same assumptions were applied.

As with the high load settings, the low variant was very consistent with respect to the amount of water used during “wash” cycle. It should also be noted that even without the heated wash, a similar amount of water was converted to vapor during the process. When dealing with the differences between the high and low settings, the first thing that should be examined is the difference in water usage throughout the entire run of the dishwasher.

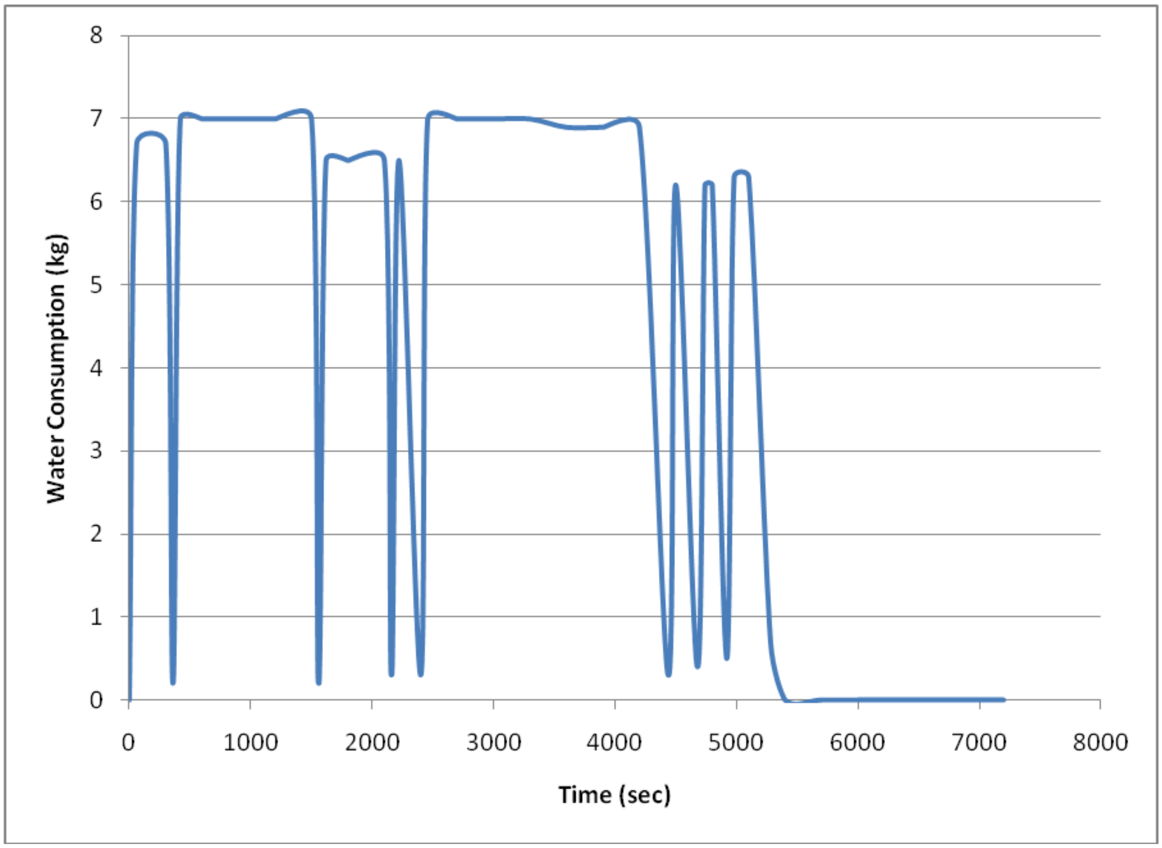

Figure 8: Water Consumption (low setting)

The low setting only has eight fills and drains, compared to the nine at the high setting. The missing drain/fill sequence occurs during the pre-wash segment of the overall cycle; therefore, for the purposes of this model, it does not play a significant role.

Regardless, it should be noted that the amount of water taken into the system at any one time does not change, only that the system uses the same water for a longer period of time during that pre-wash sequence.

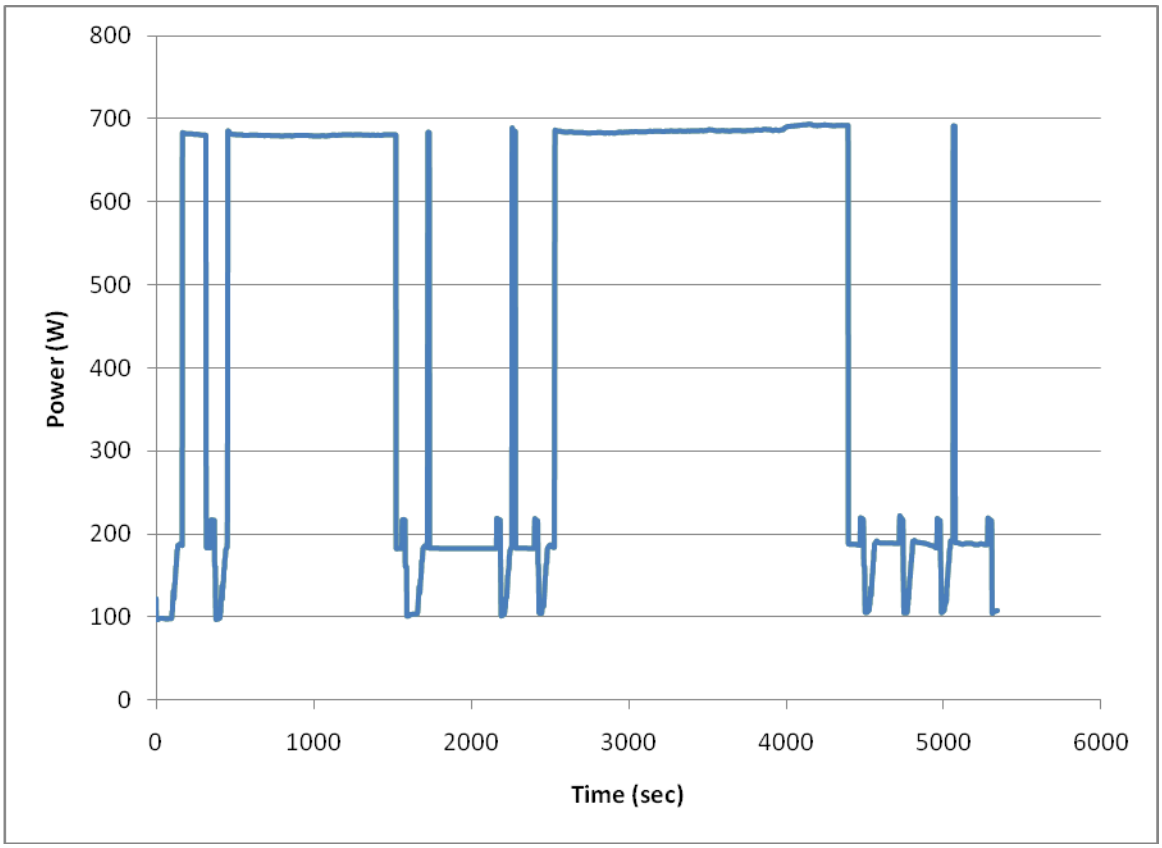

Figure 9: Power Consumption (low setting)

The energy input into the system during the wash cycle at the low setting appeared to be the same as the high setting with the exception of one spike during the "pre wash" phase around 2000 seconds, as seen in Figure 8 (compared with Figure 5). Similarly to before, the water gained 16.78 kJ of availability, an effectiveness of 1.3%.

Of the 1276.33 kJ of energy/exergy supplied to the system by the electricity, 335.6 kJ of energy and 321.32 kJ of exergy is unaccounted for. The minimal loss for this configuration, assuming only the change of state of the water and heat loss, is 913.95 kJ. This results in a maximum theoretical effectiveness of 28.4% in order to just raise the temperature of the fluid.

Irreversibilities were also very similar, as would be predicted since the cycle seemed to be the same as before. The dominant avoidable loss was in the heat transfer from the coil to the fluid, at 23.23 kJ. The irreversibility caused by the heat transfer from the system to the surroundings was 1.06 kJ, similar when compared to 1.15 kJ in the high setting. Also when summed, over all components of this cycle, 321.32 kJ of availability is unaccounted for.

Table 10: Properties and Preliminary Calculations (low setting)

	State 1		State 2	
m	6.6		6.6	kg
x	0		0.0303	
T	35.504		45.949	C
u	148.6578		260.3581	kj/kg
s	0.5117		0.878	kj/kg-k
To	25		25	C

Input E	1276.333	kJ
change in ex	16.783	kJ
eff	0.01314939	
	1.31%	

Table 11: Irreversibilities (low setting)

Exergy of Electricity	1276.343 kJ
Exergy Change of Water	16.783 kJ
Irreversibility of Coil	23.22656 kJ
Irreversibility of Heat Transfer	1.062369 kJ
Unavoidable Irreversibility Associated with Heating Water	913.95 kJ
Exergy Unaccounted For	321.3211 kJ

4.3. Comparison

The dishwasher's entire run is best modeled as an open system with mass transfer across the boundaries, but for any particular segment can be considered a closed system with the intake and exhaust solenoids closed. The wash cycle was examined because it is the part of the entire run that is meant to accomplish the overall design requirement of the dishwasher; to clean dishes. Detergent was not used in order to provide a controlled thermodynamic system that could be observed and analyzed with ease. The cycle is also a transient one, since equilibrium is never reached within the allotted time.

As can be seen from the previous presentation of results for the two setups, high HLO) and low (LLO), used to show the range of operation during the wash cycle, very few differences are seen between the two configurations. The key difference between the two setups s the amount of water used. The high setting using 14.9 gallons and the low setting used 12.8 gallons, a difference 2.1 gallons. Overall energy usage is also similar, except that the drying stage is not used during LLO. Even with the high temperature wash and dry off during the LLO, the dishwasher used almost the exact same amount of energy as in the high setup.

One of the preliminary tests was run with the heating coil physically disconnected from the system, with the other parameters set for the LLO cycle. While analysis of this test data identified that there was a problem with the cold junction compensation, CJC, so that the temperature profiles were too low, the trend is water temperatures during the overall process was established. From this profile that is shown in figure 10, it can be demonstrated that the temperature of the fluid did not significantly drop during the wash cycle. The problem with the cold junction compensation was corrected for all further testing.

One of the preliminary tests that were run involved the same setup as the LLO with the addition of removing the heating coil from the system. It was removed by disconnecting the leads used to energize it. Temperature profiles were taken, and it was at this time that two notable observations were made. The first involved the actual setup. The cold junction compensation, CJC, was not correctly set so the temperature readings were too low. The CJC was later corrected using appropriate techniques. The second observation was a trend. Throughout the overall process the working fluid did not lose much temperature as can be seen by the following figure.

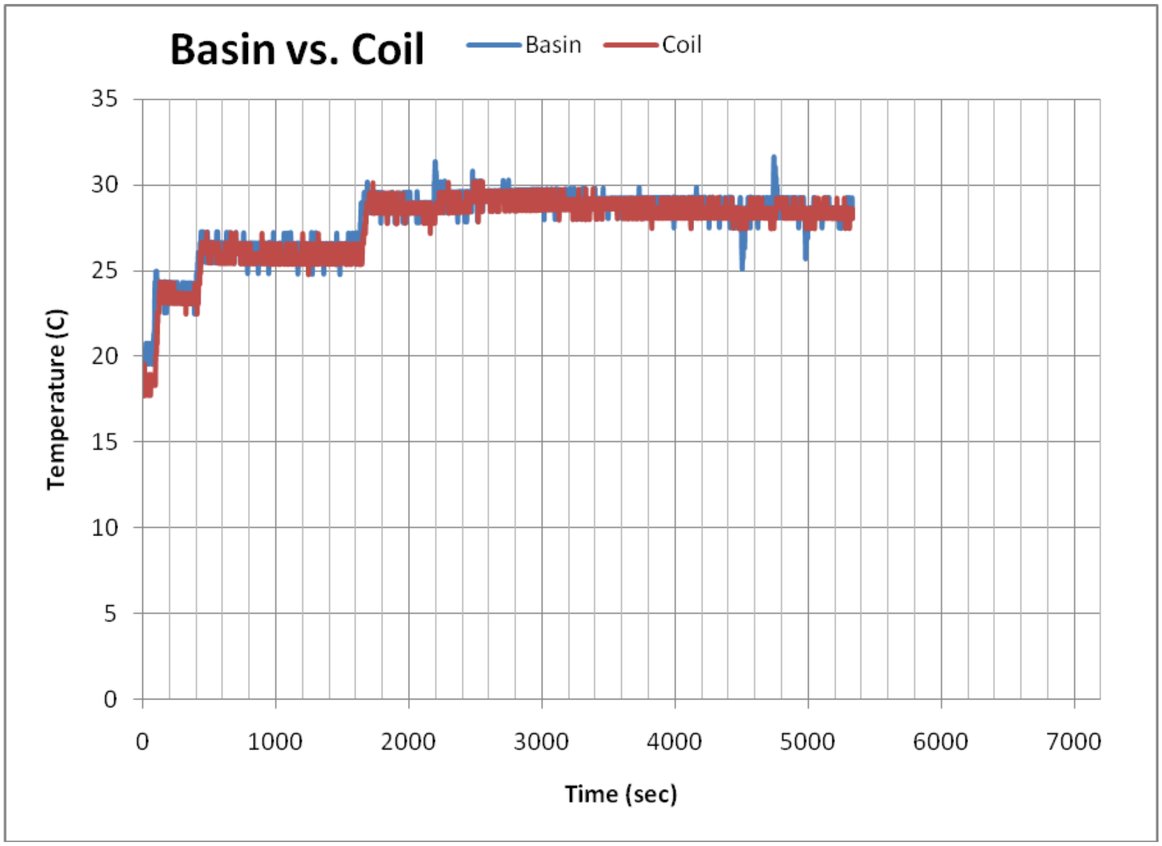

Figure 10: Temperature Profile (no coil)

The time between roughly 2500 and 4500 seconds represents the "wash" cycle. It can be seen that just moving the fluid around within the case is sufficient enough to hold the water at its inlet temperature. This observance raises a few questions, mostly in part because the coil during HLO and LLO setups did not raise the water to a steady state temperature, but simply just raised the temperature. What is the purpose of the heating coil being on during the washing cycle? If it is meant to hold the fluid at a certain temperature, then it would be logical that the fluid be heated before entering so that less energy was required over the cycle. Unfortunately, because the CJC needed correction and the temperatures were too low, an appropriate exergy analysis was unable to be conducted.

CHAPTER 5: DISCUSSION

A second law analysis serves as a means to evaluate how well a system is using a given amount of energy. This effectiveness provides a quantifiable way of representing quality. It is a tool for minimizing waste in both materials and energy, a common goal for sustainable design. Efficiencies were evaluated for a dishwasher and extracted from previously published work for a cell in order to provide a reasonable thermodynamic comparison. Exergy losses were also calculated for the dishwasher in order to provide a means for proposing improvements.

Performing an exergy analysis is presented to be a simple endeavor; however, complexity can easily add to the difficulty. As was seen in chapter 2, the exergy analysis within the cell had to take many internal interactions into consideration. Difficulty also arises when a comparison is made between the two systems. Interactions such as the ion concentration and dilution play a much larger role respectively at the cellular level than that at the dishwasher level. As engineers approach micro and nano systems, interactions like these start having an effect. Because of this, approaches need to be taken into evaluating those effects so that exergy analyses can be conducted on that respective scale. There were also effects that were unobserved in the model of the dishwasher. In the HLO configuration, 631.2 kJ of energy and 615.88 kJ of exergy are unaccounted for.

Also, in the LLO configuration, 335.6 kJ of energy and 321.32 kJ of exergy are unaccounted for. Part of the reasoning behind this is the fact that the motor-pump assembly was not able to be addressed, and another factor could have been more heat loss through the front and bottom of the case. This additional heat loss is not expected to have contributed much to the overall loss because of how low the irreversibility was for the sides, back, and top of the case. Obviously the effect of other interactions within the dishwashing system had a significant role in the effective use of energy.

5.1. Dishwasher Model

The main function of a dishwasher is to clean dishes; however, with no definitive standard for what a clean dish is, evaluating the true effectiveness is difficult. For that reason it was modeled as a basic thermodynamic system that is responsible for transferring energy from electricity to a fluid (water) in the form of kinetic motion and heat.

The wash cycle was modeled as a closed control mass with heat transfer to the surroundings. In the complete sequence of events, this is the interim between two flow stages, when the water enters and later when the water exits, and makes up only a portion of the entire running cycle. Within the assumptions made, a second law thermodynamic model was applied to the wash cycle of the dishwasher in order to evaluate how effectively the system utilizes the availability of the energy it is provided.

Reviewing the findings, the effectiveness of heating the water was small, just over 1%. It was also shown that this low effectiveness resulted from three major contributors: heat transfer to the fluid, heat transfer from the fluid to the surroundings, and the motion of the fluid molecules being sprayed about and impacting the internals. With the large percentage of exergy unaccounted for, other irreversibilities were most likely present as well.

5.2. Cell Model

The main function of one of the processes within the cell is to produce the molecule ATP as mentioned in the references in the background section. The cell creates this molecule through a series of biochemical reactions. Ultimately, it takes the energy from several sources, glucose, oxygen, and reused inorganic phosphate, and converts it to molecules of ATP, water, and carbon dioxide; the latter two having very low availability content.

Within the cell there are a number of complex interactions, each having an impact upon how the energy is transferred. While the cell as a whole is a very complex open system, with materials constantly being transported across the boundaries, it can be modeled as a closed system at a given spatial and temporal conditions. As with the dishwasher, all interactions are time dependent

During the generation of ATP from glucose, 58% of the availability is effectively transferred.[19] Also, the breakdown of palmitic acid into ATP is accomplished with an effectiveness of 60%. The irriversibilities within the cell arise from the aforementioned "complex interactions." The cell is able to undergo these conversions without a massive drop in availability. Not mentioned in the presented references, but a factor nonetheless, is that heat is released by the reactions. It is this "waste heat" that is responsible for maintaining internal temperatures. Also since reaction rates are temperature dependent, this would most likely have some effect on the effectiveness of ATP generation. Because the temperature within the system is maintained at a near isothermal condition, irreversibilities due to heat transfer are low.

5.3. Cell vs. Dishwasher

It is important to investigate the exergy efficiencies associated with the respective systems, since these values serve as a normalized value which is able to be compared. The processes within the cell addressed within this thesis, are able to achieve a much higher overall effectiveness through a larger number of energy transformation events. This is compared to the dishwasher having a very low effectiveness, when it only undergoes a handful of energy transformations. It converts energy from electricity to heating and kinetic energy of the water.

While energy transformations and the use of water are common to the two systems detailed comparisons of the parallels between the two are difficult to undertake. However, some general comparisons can provide preliminary insights for future studies in the use of biology as a tool for engineering design. A cell has pumps, material and energy transfers, and is able to exist with a solid, yet permeable boundary with the surroundings.

Table 12: Dishwasher vs. Cell

	Cell	Dishwasher
Boundary	Cell Membrane	Plastic Case
Inlet Driving Force	Diffusion	Pressure Gradient
Outlet Driving Force	Diffusion	Pump
Amount of Material Used	As needed	Pre-defined amount
Driving Energy	ATP	Electricity
Energy Source	self made	supplied

The cell operates on an as-needed basis based on the materials available and the temperature at which the materials are located, but the dishwasher uses a pre-determined set standard regardless of requirements. Regulatory proteins within the cell are able to sense the current conditions and requirements of the cell and act accordingly as either an inhibitor or catalyst. The dishwasher operates on a fixed cycle based upon time.

Heating the water causes a significant exergy loss, so reducing the need for the water to be heated would significantly reduce the irreversibility and required energy. As the change in temperature approaches zero, so does the loss in availability. Reducing the heat transferred to the surroundings would have a similar effect of reducing the loss in exergy, although the loss due to heat transfer to the surroundings is on the order of three magnitudes less than in the actual heating.

Recent models of dishwashers have taken these issues into consideration and newly revised standards have been placed on the systems. ENERGY STAR serves as a standard for water and energy use for many appliances, including dishwashers. Manufacturers, such as Bosch, have placed various sensors within the system in order to determine the amount of water/heat needed and adjust accordingly. Some sensors are even capable of sensing the soil level of the water and adjusting the cycle length if the dishes become clean before the prescribed time. Heating has also seen a change. Some units are capable of heating the water in-line rather than by placing a coil in the basin, others are able to use a heat exchanger approach and use the waste heat from the previous cycle to heat a reservoir of water to be used in the next cycle. These methods reduce total energy consumption and reduce the change in temperature, both resulting in increased exergy efficiencies.

According to a review on "new Bosch dishwashers," Bosch has added multiple means for reducing both energy and water usage.[23] "EcoSense" is a system that uses a sensor to determine the soil level of the wash water and automatically adjusts subsequent water usage. A second feature is named "Eco Action" and is capable of reducing the water temperature and extending the wash time, resulting in less energy usage. Means of heating have also been changed through the use of two different kinds of heating. The first is a "Flow-Through Water Heater" which is responsible for heating incoming water through direct contact with the element, resulting in faster, more efficient heating. The second heater is a "Concealed Heating Element" and is used to maintain and/or control the temperature during the cycles. The system used in the model utilized an elevated heating coil at the bottom of the basin, relying on the sprayed water hitting it in order for direct heat transfer to occur. There is also mention of the possible use of a heat exchanger. The exchanger houses a volume of water for the next fill and uses the waste heat from the previous cycle running to heat the reservoir. Drying was not addressed in the scope of this model, but it is to be noted that the system used in the model attempts to dry the dishes by raising the temperature of the heating coil up to around 340-350 °C. It can be seen by the temperature profiles in Figure 3 that this high coil temperature results in a maximum temperature of 58-65 ° C at the locations of the upper and lower drawers. The Bosch system utilizes the fact that the case is constructed from metal to create a condensation effect, pulling the water from within the system to the walls of the case. Another method is the use of zeolith minerals to extract moisture from the system. Each of these modifications can be related back to the on-demand behavior of the biological cell, where actions are responses to information sensed by the regulatory proteins.

5.4. Design Potential

The use of exergy relationships presents a useful tool for engineering design. By designing for an effective use of energy and materials, efficiency will surely follow. It provides a means of quantifying the losses of useful energy and the effective use of the available energy. Engineers have been designing for years through biomimicry, by looking to nature for inspiration. The cell is a dynamic machine that has many components operating in unison for the purpose of fulfilling the operational function of the cell. It is able to do this with minimal waste of available energy and materials. The molecules of ADP and inorganic phosphate are continuously being recycled through the ATP synthesis and hydrolysis reactions. A particular type of cell or organism may provide specific insights into where functionality and performance can be improved for an engineering design by mimicking the related effectiveness of the cell components.

While aspects of sustainability have recently been incorporated into design software such as SolidWorks; this tool only addresses the amount of use and not the effectiveness of the use of resources. If 1000 kJ of energy is 100% efficiently used to heat a reservoir of water through some change in temperature, the end result is still a loss in work potential of that water. In other words, the second law of thermodynamics establishes that the energy provided to heat the water could never be achieved by using the water to drive a generator or some other device. By minimizing these wastes, more can be accomplished with a set amount of energy. When applying the "Twelve Principles of Green Engineering," this work demonstrates that Principles six and twelve can be addressed using an exergy approach. As previously stated, whenever energy is transferred an amount of available energy is lost. The can be viewed, like Principle six, as an entropy investment. Principle twelve states that materials and energy should not be depleted; therefore, the use of these resources should be optimized to maximize their effectiveness.

By using the LCA methods previously discussed in chapter two, along with the appropriate exergy relations, a full evaluation of the product can be made. The LCA analysis identifies material and energy use throughout the life cycle of the product, and the exergy relationships evaluate how effectively the energy and materials are used. The key to creating appropriate design metrics is to combine these two methods into a readily determined term or guideline, like the previously used Energy Factor, that can be incorporated into design methodologies and software tools.

5.5. Future Works

With the ultimate goal of this work resulting in design metrics, how would the information presented here be of use in achieving this goal? The answer is: currently it cannot be directly related. In order for engineers to use the information known about a cell to better design products, a closer look within the systems of a cell must be made. It is still necessary to investigate how the cell converts energy to achieve the exergy efficiencies it does.

Design metrics serve as guidelines for engineers to follow during the design process of a product so that they can achieve the desired result within a particular range of acceptable values. The dishwasher is an example where a design metric for water heating could be used. By having a metric designating that for water heating a process must have an effectiveness of at least X amount, or that the process can only have an acceptable irreversibility of X, a large portion of the loss in availability can be eliminated or at least alleviated.

More appropriate comparisons are possible by considering systems within a cell and finding their relative counterpart in the macroscopic. Molecular motors such as kinesin and myosin would be comparable to systems in the macro that relate to motion from winches and vehicles. The protein pumps that transfer materials across the membranes of the cell also serve as another point of comparison. The entire ATP generation as addressed in this thesis could also be related to power generation plants.

Regardless of the comparison, the cell serves as significant source for possibilities in improving energy and material utilization.

CHAPTER 6: CONCLUSION

The model presented within this thesis provides a foundation for future works for creating design metrics based on comparisons between biological systems and mechanical systems with exergy serving as the link. The experimentation revealed that there are many losses of available energy found within a dishwasher, resulting in very low effectivenesses. Heating water contributes a significant loss, as does raising the temperature of a mass of water. Further study of the unaccounted losses could show areas of the system, besides the heating of water, that contribute to the overall low effectiveness of the system.

When compared to the biological cell, the cell showed higher effectivenesses in the conversion of glucose and palmitic acid to ATP. The goal for future studies is to harness this observation and be able to appropriately parallel it with a mechanical system. If engineers are able to mimic these results at the macro level, then the result will be increased sustainability of resources and energy in a society that is steadily increasing its demand.

Strides are currently being taken both in industry and through government agencies to promote sustainability. In industry, designers are focusing on environmental impacts through LCA and agencies such as the EPA are promoting standards such as ENERGY STAR to reduce energy and material waste in dishwashers. Currently there are no regulations in place in the US such as the café standards imposed on the automotive industry. By combining these technologies and standards with LCA analyses and exergy metrics, not only will less energy and material be used, but the energy and materials that are used will be used more effectively.

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APPENDICES

Appendix 1: Experimental Setup Photos

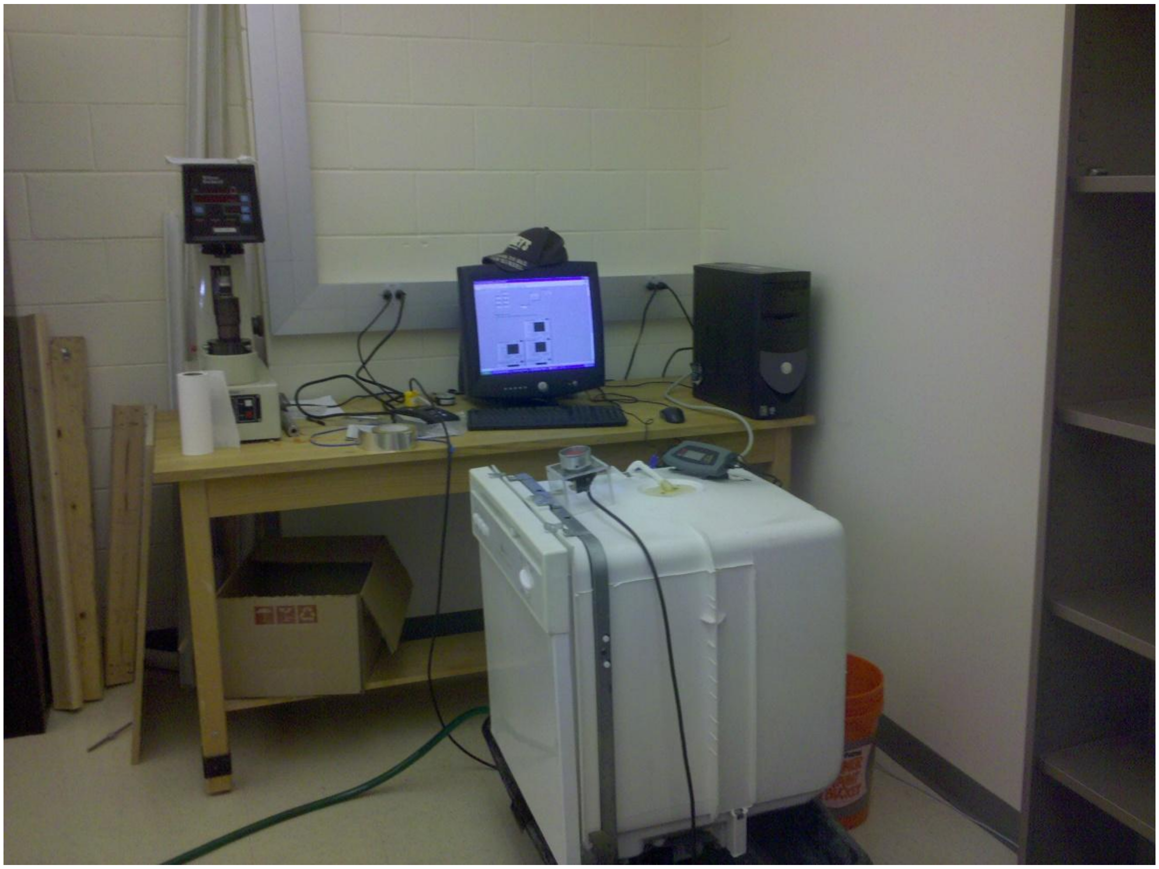

Figure 11: Overall Setup (side view)

Appendix 1 (Continued)

Figure 12: Overall Setup (front view)

Appendix 1 (Continued)

Figure 13: DAQ with Thermocouples Connected

Appendix 1 (Continued)

Figure 14: Internal View with Thermocouples

Appendix 1 (Continued)

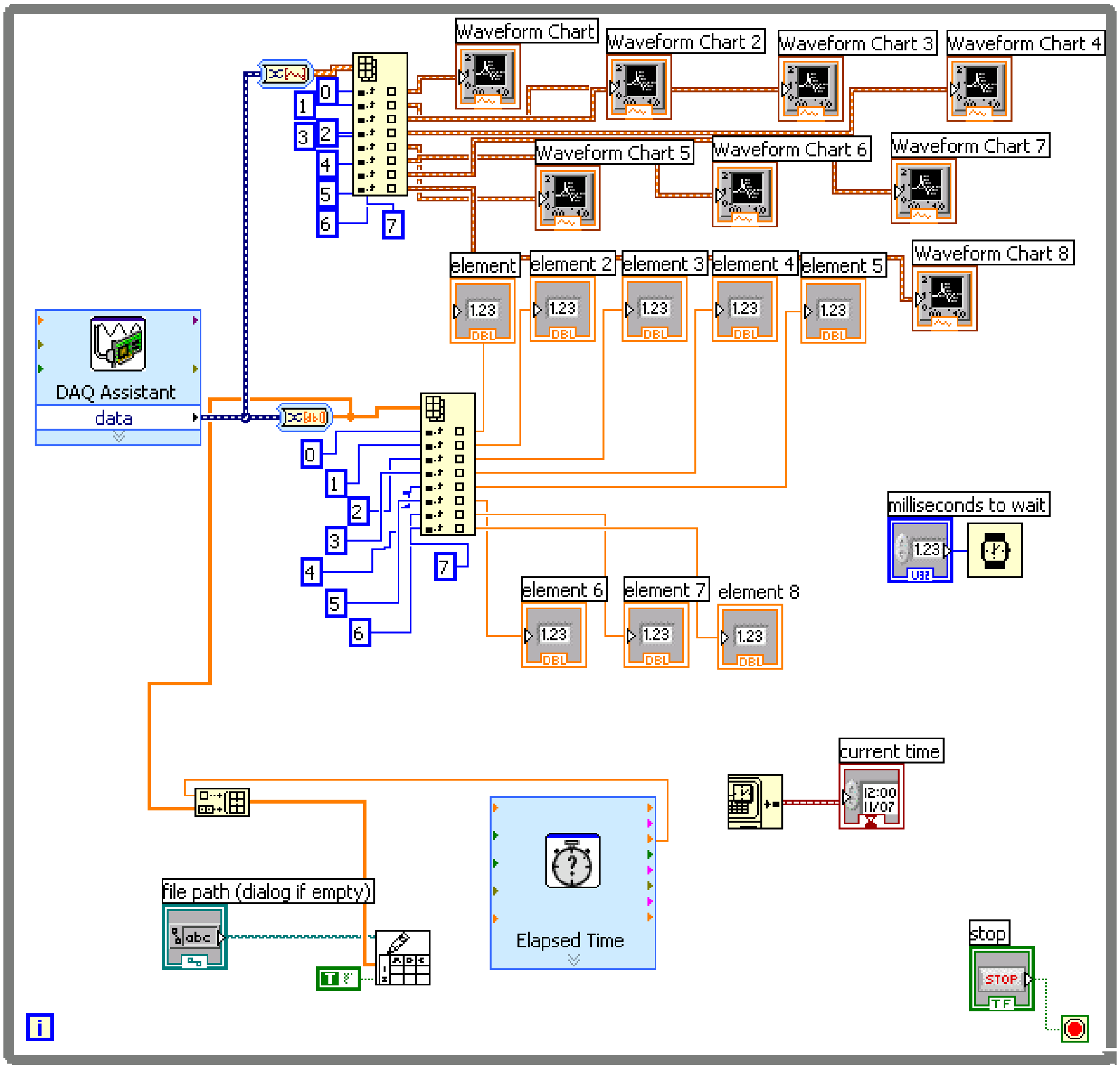

Figure 15: Labview Block Diagram

Appendix 1 (Continued)

Figure 16: In-Line Flow Meter

Figure 17: Watts Up? Power Meter

Appendix 2: Sample Data Set

Table 13: Excerpt Sample Data Set (high setting)

time (sec)	Top Drawer	Out case	In Case	Bottom Drawer	Coil	Basin	Intake	Exhaust	Q kJ	I coil	Q wall W	Q wall kJ	I wall	Q/T
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2422	39.592	37.844	39.59	39.592	51.66	39.01	37.26	32.563	0.976	0.036263	123.4782	0.246956	0.001322	0.000794
2424	39.592	37.844	39.01	38.427	46.52	39.01	37.844	32.563	0.976	0.021882	82.36587	0.164732	0.000589	0.00053
2426	39.01	37.844	39.01	39.01	49.95	39.592	37.844	32.563	0.976	0.029803	82.36587	0.164732	0.000589	0.00053
2428	39.01	37.844	39.01	39.01	49.95	39.01	37.844	33.152	0.976	0.031536	82.36587	0.164732	0.000589	0.00053
2430	39.592	37.844	39.01	39.01	49.95	39.01	37.844	31.972	0.976	0.031536	82.36587	0.164732	0.000589	0.00053
2432	39.01	37.844	39.59	39.592	49.95	38.427	37.26	32.563	0.976	0.033278	123.4782	0.246956	0.001322	0.000794
2434	38.427	37.844	39.01	39.592	49.95	38.427	37.26	32.563	0.976	0.033278	82.36587	0.164732	0.000589	0.00053
2436	39.592	38.427	39.01	39.592	53.36	39.01	37.26	33.152	0.976	0.040924	41.18294	0.082366	0.000147	0.000264
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 14: Water Usage Sample (high setting)

time(min)	time (sec)	gal	mass
0	0	133	0
5	300	134.8	6.5
10	600	136.6	7
15	900	136.6	7
20	1200	136.6	7
25	1500	136.6	7
30	1800	138.3	6.1
35	2100	139.9	6
40	2400	141.4	6
45	2700	143.1	6.7
50	3000	143.1	6.7
55	3300	143.1	6.7
60	3600	143.1	6.6
65	3900	143.1	6.6
70	4200	143.1	6.6
75	4500	143.1	0
80	4800	146.3	5.9
85	5100	147.9	6.2
90	5400	147.9	0
95	5700	147.9	0
100	6000	147.9	0
105	6300	147.9	0
110	6600	147.9	0
115	6900	147.9	0
120	7200	147.9	0

drain	time	mass		fill	time	gal	mass
				x	120	134.8	6.5
x	360	0		x	420	136.6	7
x	1560	0		x	1620	138.3	6.1
x	1920	0		x	1980	139.9	6
x	2160	0		x	2220	141.4	6
x	2400	0		x	2460	143.1	6.7
x	4440	0		x	4500	144.7	6.2
x	4680	0		x	4740	146.3	5.9
x	4920	0		x	4980	147.9	6.2
x	5280	0					

Appendix 3: Sample Calculations

$$\Delta E_{CM} = Q + W$$

$$m\Delta u = Q_{HT} + W_{supply} + W_{motion,etc}$$

$$W_{motion,etc} = m\Delta u - Q_{HT} - W_{supply}$$

$$W_{motion,etc} = 6.7[kg] * (230.58 - 163.31)\left[\frac{kJ}{kg}\right] - (-216.91)[kJ] - 1298.94[kJ]$$

$$W_{motion,etc} = -631.32[kJ]$$

$$\Delta\Phi_{water} = m(u_2 - u_1) - mT_0(s_2 - s_1)$$

$$\Delta\Phi_{water} = 6.7[kg] * (230.58 - 163.31)\left[\frac{kJ}{kg}\right] - 6.7[kg] * (24.5 + 273)[K] * (0.7772 - 0.5589)\left[\frac{kJ}{kg * K}\right]$$

Appendix 3 (Continued)

$$\Delta\Phi_{water} = 15.58[kJ]$$

$$Q_{wall} = -kA\frac{dT}{dx} = -kA\frac{(T_{inside} - T_{outside})}{t}$$

$$Q_{wall} = -0.17\left[\frac{W}{m*K}\right]*1.3193[m^2]*\frac{(37.26-36.09)[K]}{0.003175[m]}$$

$$Q_{wall} = -82.65[W]$$

$$Q_{wall} = -0.17[kJ]$$

Appendix 3 (Continued)

$$I_{coil} = Q_{coil} T_0 \left(\frac{1}{T_{CM}} - \frac{1}{T_{coil}}\right)$$

$$I_{coil} = 0.976[kJ] * (24.5 + 273)[K] * \left(\frac{1}{(38.43 + 273)} - \frac{1}{(45.95 + 273)}\right)\left[\frac{1}{K}\right]$$

$$I_{coil} = 0.022[kJ]$$

$$I_{HT} = Q_{HT} T_0 \left(\frac{1}{T_{outside}} - \frac{1}{T_{inside}}\right)$$

$$I_{HT} = 0.17[kJ] * (24.5 + 273)[K] * \left(\frac{1}{(36.09 + 273)} - \frac{1}{(37.26 + 273)}\right)\left[\frac{1}{K}\right]$$

$$I_{HT} = 0.0006[kJ]$$

$$I_{process} = T_0 \sigma = T_0 \left(m\Delta s_{CM} - \sum \frac{Q_{HT}}{T_{outside}}\right)$$

$$I_{process} = (24.5 + 273)[K] * \left(6.7[kg] * (0.7772 - 0.5589)\left[\frac{kJ}{kg * K}\right] - (-0.69)\left[\frac{kJ}{K}\right]\right)$$

$$I_{process} = 640.40[kJ]$$