Energy Conversion Loop: A Testbed for Nuclear Hybrid Energy Systems Use in Biomass Pyrolysis

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Authorization to Submit Thesis

This thesis of Kelley Marie Verner, submitted for the degree of Master of Science with a major in Biological Engineering and titled “”Energy Conversion Loop: A Testbed for Nuclear Hybrid Energy Systems Use in Biomass Pyrolysis,” has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Nuclear hybrid energy systems are a possible solution for contemporary energy challenges. Nuclear energy produces electricity without greenhouse gas emissions. However, nuclear power production is not as flexible as electrical grids demand, and renewables create highly variable electricity. Nuclear hybrid energy systems are able to address both of these problems. Heat can be used in processes such as desalination, hydrogen production, or biofuel production. This research explores the possible uses of nuclear process heat in bio-oil production via biomass pyrolysis. The energy conversion loop is a testbed designed and built to mimic the heat from a nuclear reactor. Small scale biomass pyrolysis experiments were performed and compared to results from the energy conversion loop tests to determine future pyrolysis experimentation with the energy conversion loop. Further improvements must be made to the energy conversion loop before more complex experiments may be performed. The current conditions produced by the energy conversion loop are not conducive for biomass pyrolysis.

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CHAPTER 1

Introduction

In the United States 66% of all electricity produced was from fossil fuels in 2015 [1]. The concern of global warming and greenhouse gas (GHG) emissions have sparked the demand for carbon neutral energy sources. Between the environmental problems and the desire to be energy independent, there is a high demand for alternative energy sources all over the world.

Alternative energy producers include wind, solar photovoltaic (PV), hydroelectric, and nuclear power. These are only a few options for electricity production but are well known and mature technologies. Each alternative energy producer has drawbacks; renewables like solar and wind are highly variable and take up large amounts of land, while nuclear has very dangerous waste products and reactors cannot easily fluctuate to follow the electrical loads demanded. To mitigate some of these challenges, nuclear hybrid energy systems (NHES) have been proposed [2,3]. Traditional hybrid energy systems (HES) are the combination of at least two energy producers used together to produced energy commodities. HES are an attractive way to diversify the energy portfolio making electricity production not only more flexible but more reliable. NHES are a special type of HES that include a nuclear power plant (NPP) as one of the energy producers.

NHES can fluctuate power and follow the load demanded of it by diverting electricity or heat from the NPP to another process. As can be seen in the diagram below (figure 1.1), the energy from both power producers can be sent to the grid when demand is high, or when the renewable electricity supply is insufficient. When demand is low and the renewable source can provide what is needed, the energy can be taken from the NPP and used in a process heat application.

Many process heat applications exist and have been explored with the use of NPP. These include desalination [4], fossil fuel processing [5,6], hydrogen production [7,8] and biofuel production [9]. In the literature review, the largest focus appears to be on desalination and

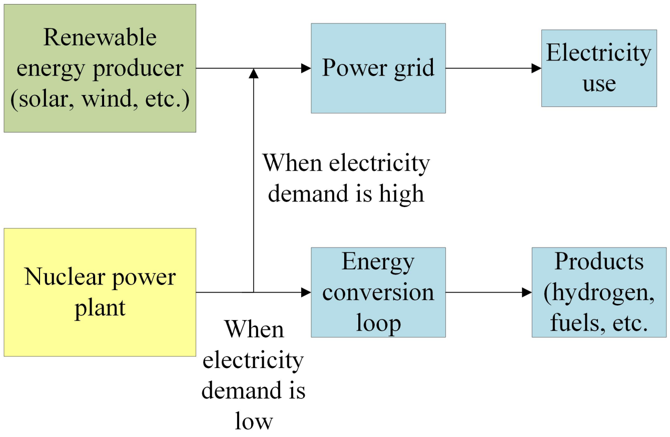


Figure 1.1: NHES configuration and energy flow

hydrogen production. Little research has focused on biofuels. The purpose of this research is to explore the possibility of creating biofuels from the process heat. These fuels are created from a biomass of some sort; wood waste, agricultural waste, etc. This can be done via many methods but the focus of this research is on pyrolysis of biomass. Pyrolysis is the heating of a material in the absence of oxygen. The material is thermally broken down into oils, vapors, and char. Depending on the conditions, the liquid oil product, bio-oil, can be optimized and used for fossil fuels alternatives and many other products. Pyrolysis can readily convert complex molecules like lignocellulose to bio-oil and uses wastes rather than valuable food sources.

As previously stated, load following power is a current challenge of NPP technology. The system designed and built for this research is called the energy conversion loop (ECL). It is a testbed for different process heat applications that could be used with an NHES. The small size allows for early testing of different processes such as desalination, hydrogen production, and many processes that require heated steam or air. The full design and analysis will be included in later chapters.

CHAPTER 2

Literature Review

2.1 Hybrid energy systems

HES are two or more energy producers combined to create energy products, for example combining a solar farm and a wind farm together to produce more electricity. This example is extremely simple and much more complicated options are being considered. The methods of consideration are technical, economic, and environmental. In the literature each study is very different. However, the biggest distinction between studies is the proposed use of the HES. The two largest categories are HES for small, rural energy production and HES for large-scale energy production.

HES for rural areas of the world are a promising way of bringing energy to remote places in an affordable and practical way. In a study performed by Adaramola, Agelin-Chaab, and Paul [10], an HES made of solar, wind, and diesel generators was proposed for use in southern Ghana. Using HOMER, an HES modeling software, it was determined that the combination of PV arrays, wind energy, and generators was the best option technically and economically. This configuration created 791.1 MWh/year with the cost of only \$0.28/kWh. This is enough electricity to meet the demand and is a viable option for the small community. Another simulation of solar energy, biogas energy, batteries, and multiple types of generators (diesel, biomass, and micro-hydro) was studied in Narendra Nagar block of the Uttarakhand state. The simulations varied the infiltration of solar energy produced from 0% to 100% with increments of 20%. All of the simulations were able to produce the needed 1271.61 kWh/day, but the most economic option (\$0.09/kWh) used 20% PV power [11]. Shin et al. [12] used linear programming to determine the best HES for Deokjeok Island. Solar was the main energy producer in this HES and the final combination was solar PV, wind, batteries, and diesel generators. The cost of energy was \$0.239/kWh, and the energy produced was 8,667,7400 kWh/year or 23,746 kWh/day. All of these examples showed the possible value of HES in rural and isolated areas, but little work has shown on the actual experimental setup of these.

Other studies are more general and focus on large areas in need of electricity production. In these cases, it is important to first simulate and establish what configuration of HES works best for the available energy sources. These studies also propose many different combinations of energy producers based on the country's capabilities. Borges Neto et al. [13] proposed using solar PV and biogas from anaerobic digesters in areas of Brazil where electricity is unreliable or non-existent. Goodbody et al. [14] proposed using HES throughout Ireland based on the geographical location. The country was broken up into smaller areas depending on what renewable energy source is best able to meet the needs of the people in the area. Similar simulation and modeling studies were performed to determine what HES is best for a small area in need of inexpensive and reliable electricity [15–17]. On national levels many HES configurations have been investigated. These include the use of geothermal energy using ground source heat pumps combined with other renewable producers in China [18], solar-biomass power plants in India [19], and wind and solar power conversion [20].

Previously explored examples all used modeling to determine the how to use the HES but few studies have used simulations and physical models to determine the use of the HES. Pérez-Navarro et al. [21] built a simulation laboratory called LABDER. Here they can model and experiment with different combinations of energy producers. In the study, two HES were explored; PV panels, biomass gasifier, and a battery storage bank, and the second experiment involved all the previously mentioned technologies and added a wind generator. Both configurations were able to supply the residential electricity demand. Another experimental study found the use of PV arrays connected to batteries, an electrolyzer, and fuel cell were a plausible option for residential electricity production [22]. Physical experiments like these are rare in the literature.

HES are a great way of providing reliable and efficient energy. By combining multiple energy producers the concerns of fluctuating and variable electricity can be mitigated.

Though HES are a good solution to many problems there are shortcomings. A huge concern is the economics of HES due to the high capital costs. There also needs to be breakthrough technologies that increase the efficiency of technologies, such a solar PV. The last challenge is the need to adapt to large electrical load fluctuations [23]. All of these challenges are extremely important and must be addressed if HES are going to have a possible future, but also illustrate the benefits of diversifying the energy portfolio.

2.2 Nuclear hybrid energy systems

Much like traditional HES, NHES create stable, environmentally responsible, and sustainable energy resources. By having a diverse energy portfolio these goals can be achieved [24]. Renewables and nuclear alike have their own sets of challenges. Renewable energy producers are highly flexible and intermittent depending on the time of day or year. Nuclear energy is primarily a baseload power source, so load following power is difficult to create [2, 8, 24–27]. Baseload power is considered to be 2/3 of the power demand. This is due to physical and economic limitations. Baseload producers give out a constant level of power and do not fluctuate. Load following power is the ability of the producer to supply the electricity to consumers as the demand rises and falls [2]. NHES can create the needed load following power with the baseload producer and flexible renewables. As is shown below, the basic idea of how to create the load following power is the same for all NHES but the end products vary greatly.

Many conference proceedings involving Idaho National Laboratories (INL), National Renewable Energy Laboratories (NREL), and Joint Institute for Strategic Energy Analysis (JISEA) have articles that show the needs and future of NHES. Two separate publications from the JISEA have discussed the merits and needs for NHES. Richard Boardman of the INL presented the work analyzing the combination of nuclear, renewable, and chemical plant operations. Excess steam and electricity can be used in chemical production or industrial processes. When energy demand is high, all electricity from the NPP and the renewable source is diverted to the grid. When energy demand is low, or the renewable production is sufficient, the steam or electricity from the NPP is diverted to the industrial process. This way, the NPP does not have to ramp up and down the heat production. The NHES can continue to produce heat, but reduce the power created in order to supply the heat to industry; it can stay at the optimal output and still create something valuable [24, 26]. This is how all NHES are proposed to work. It is advantageous not only for efficiency but can offset the capital investment by creating more commodities besides electricity. The second summary report from JISEA in 2012 proposed NHES for the use of load following power, the creation of transportation fuels, hydrogen, thermal energy storage, and many other processes [2]. Lastly, in more recent conference proceedings from 2015 [3] produced by the NREL and the INL, the benefits and possibilities of NHES were discussed again. Some of the benefits are; reduction of GHG emissions, maximize the system reliability, profitability, and supply, reduction of fossil fuels from production of hydrogen, biofuels, and synthetic fuel, reduction of fresh water consumption by using desalination, solar power, and wind power, and the use of domestic natural resources to lessen dependence on imports. The proceedings may not offer a great deal of technical information but do show that NHES are a technology being considered as a viable option for reliable energy in the future.

As a physical example, Garcia et al. [28] created a multi-part series analyzing HES dynamically. Part one explores an NHES configuration made up of a small modular reactor (SMR), a steam turbine, a load following power plant, a renewable power generator, electrical storage, and an auxiliary heat generation plant. The SMR and the heat generation plant provide the steam for outside uses of process heat. This study explains that using the system for multiple energy products the electricity can be managed even further and the processes act as an electricity smoothing device. From this introductory analysis, NHES appear to be a very plausible technology and a promising way to create reliable power and diverse energy products.

2.3 NHES process heat applications

2.3.1 Fossil fuel and oil production

NPP have been proposed as the supplier of heat and electricity for different technologies concerning fossil fuels. Forsberg [5, 6] explains the advantages of using NHES for oil. Most of the usable light crude oil is in unstable countries and must be imported to the United States By using less ideal, but abundant, fossil fuels such as tar sands, oil shale, and soft coal, transportation fuel becomes more easily attainable if used with reliable heat and energy resources. The current problem is recovering and treating these fossil fuels uses large amounts of fossil fuels, creating harmful GHG emissions. By heating a fossil deposit to high temperatures, the light volatile hydrocarbons will vaporize and be distilled at the surface. Heavier hydrocarbons will go through thermal cracking and release lighter hydrocarbons to create transportation fuels.

In an INL study [29] for the state of Wyoming, products that can be co-produced with NHES, wind energy, and an NPP were explored. It concluded the best application for this would be reforming natural gas or coal to methanol to create gasoline or producing Fischer-Tropsch diesel from natural gas or coal. Normally these production operations happen in a constant fashion, but this study showed all four of these processes can be completed in a dynamic way, making it appropriate for NHES. It also demonstrated a steadying effect on wind generated power and a way to decrease the emissions created from the reforming of natural gas or coal. By using the NPP, 97% reduction of CO_2 was achieved in the models.

High-temperature gas-cooled reactors (HTGR) were explored for use with oil recovery from oil shale, desalination, and upgrading bitumen to synthetic crude oil. Desalination will be explained later in the literature review. Useful products from oil shale can be created by converting the kerogen, found in the oil shale, to natural gas and shale oil. This process requires large amounts of heat and energy. Bitumen is a substance found in tar sands and needs methane to be processed into crude oil. The oil recovery process and bitumen upgrading traditionally are done using heat and energy from natural gas or fossil fuel heat. The reduction of emissions for shale oil recovery is roughly 91%. For bitumen reforming, if steam methane reforming is used, there is a 38% CO_2 reduction and a decrease of 46% of the natural gas use [30]. Similarly, Forsberg [8] presents three uses for NHES and steam produced from it. One of these is shale oil production. This study also found a reduction in CO_2 emissions. This process does not require constant heating so it is well suited to the variable heat resource of NHES.

Garcia et al. [31] created a model to analyze the possibility of two regional NHESs. One was the combination of wind resources and NPP for electricity and production of gasoline using the excess thermal energy in Texas. It was ensured an SMR would be able to produce the peak electricity load independently from the wind farm. The outlet temperature from the SMR to the gasoline conversion process was modeled near 300°C. The configuration quickly responded to meet the electricity demand. If the wind farm can generate 85 GWh with a grid demand of 171 MW, 0.35 million tons of CO_2 are produced. These emissions can decrease if the renewable producers create more energy, and further integration of the renewables in the grid was achieved up to 30%. Models, such as these, help demonstrate the ideal conditions for NHES and what is most appropriate for a region.

2.3.2 Hydrogen production

In a study on nuclear hydrogen use with HES, Forsberg [32] illustrates the need for hydrogen, primarily for fossil fuel reforming and chemical processes. It can also be used for electricity production in fuel cells and steam turbines. Hydrogen can be created using NPP, either through electrolysis, using electricity, or through thermal methods. Thermal methods are less expensive than low-temperature electrolysis, so would be preferred over electrical means. Thermal production of hydrogen requires extremely high temperatures, as shown in a study of an HTGR use for hydrogen production. The most efficient production rates happened at very high temperatures, above 700°C. Between 1.90 and 2.12 kg/s of hydrogen were produced in the model with a 600 MW_t (thermal) nuclear reactor. This application shows that HTGR are appropriate for thermal conversion of hydrogen from water [7]. In another option, thermal and electrical methods can be combined into high-temperature electrolysis (HTE). It is more efficient than normal electrolysis and less costly. One study showed combining 2857 MW_t from a NPP and 15,438 MW_e (electrical) from the grid 120.81 kg/s of hydrogen can be created [8].

To reduce the operating temperature of HTE thermochemical methods can be used. One study compared Cu-Cl (copper chloride), S-I (sulfur iodide), and Mg-Cl (magnesium chloride). All of these processes occurred at temperatures over 500 °C. The most exergy efficient process was that used with S-I. However, this process was done at the highest temperature of 850°C, which is still very high. The other cycles were less efficient but operated at lower temperatures [33]. Similar studies were conducted to find the best thermochemical cycles for hydrogen production. Ozcan and Dincer [34] studied the Mg-Cl cycle at different temperatures. They determined that almost 7% less electrical work was needed when using Mg-Cl cycle compared to traditional electrolysis. The temperatures for this process where less than thermal conversion alone with the highest at 450°C. Jaszczur et al. [35] used Cu-Cl and S-I cycles and compared different connections to a high-temperature helium reactor. Both were able to reach an efficiency with the reactor of 50%. The electrical efficiency can reach 55% when the outlet temperature reaches 1000°C. S-I cycles were possible if the helium temperature was around 900°C. The Cu-Cl cycle required lower temperatures of about 612°C leaving the turbine; this lowers the thermal efficiency to about 37%. There is a trade-off between efficiency and temperature. Many other studies exist that agree using thermochemical water splitting is the most efficient and environmentally responsible method for hydrogen production when compared to purely thermal or electrical means [36–38].

There is a large body of work concerning hydrogen production with NPP. The ECL could be used for HTE tests below 500°C or requires supplemental heating. Because of this, the research here focuses on less well-established process heat applications.

2.3.3 Desalination

Another heavily researched use of NPP process heat is desalination. Desalination is the removal of salt and harmful contents of sea water or brine, to create fresh water. There are three main processes for desalination discussed most in the literature. Reverse osmosis (RO); this is the process of pressurizing the salt water and pushing it through a membrane against the natural flow of osmosis. The membrane captures the impurities and salts. The other two desalination techniques are distillation based; multi-effect distillation (MED) and multi-stage flash distillation (MSF). Much work is being done to perfect different techniques of desalination and address concerns. The main concerns are the use of too much energy, the desire for higher recovery of fresh water, and cost.

Many renewable energies have been investigated for use with desalination. A recent study [39] used solar energy for desalination using an air bubble column humidifier; this technology uses heated air to heat saline water and distill the fresh water out of the saline water. This form of desalination uses very little energy and low heat, 63% recovery was achieved. Kim at al. [40] focused their work on RO plants combined with an HES. The HES was composed of a primary heat generator (PHG), thermal-to-electrical conversion, a renewable power source, energy storage, a power grid, and a freshwater production plant. Solar PV energy and wind energy were modeled as the renewable sources. Four case studies were done and from these, the results showed several important findings. The amount of salt removed from the water was not adversely affected by the change in power to the grid or to the RO plant. Providing energy to the grid and the RO process was easily done with both PV and wind energy. The most economic option was to create freshwater when electricity demand was low due to the higher value of freshwater to excess electricity. These findings are important not only to renewables but NHES as well. Applying this to an NPP would also be feasible.

Several studies have looked at using heat from other processes for thermal desalination.

MED was demonstrated by Zhao et al. [41] in a study where the number of effects in the system were varied. The number of effects increased the amount of clean water created but had a negative effect on steam quality. This study used steam temperatures of 70 to 130 °Cfrom an oil refinery. Maneti et al. [42] proposed using MED with geothermal plants to efficiently create fresh water. Both of these uses of steam are comparable to the heat from an NPP in that it is the process heat. The MED process used in these studies could be used with NHES.

These previous studies only looked at desalination but not desalination coupled with NPP. NuScale SMRs are reactors made up of many small modules; each independently produces steam and energy. One study focused on how to couple the SMR technology with desalination technologies. RO plants rely mostly on electricity production while the distillation techniques rely on the steam coming from the reactor. Both types of desalination are able to couple with one module. By combing the MED with a thermo-compressor, and using the high pressure steam, 88,000 m^3/day of fresh water were created from one module. The turbines were then sized based on the steam's abilities after being used for distillation. However, as the amount of clean water was increased the electricity output was decreased. Using low pressure steam and a back-pressure turbine water, production of 51,000 m^3/day was modeled. An RO plant was also modeled with the SMR. For each option to produce the same amount of water the RO plant created the most electricity and fresh water, making RO the best option to pair with the SMR [4].

A similar feasibility study was conducted and the results agreed with the NuScale SMR results. A 200MW integrated nuclear heating reactor (NHR-200) was considered with three desalination processes; low-temperature horizontal tube evaporator (MED-TVC), high-temperature vertical tube evaporator (VTE-MED), and a combination of RO and MED. The MED-TVC option could produce 107,500 m^3/day of clean water. The VTE-MED option produced 160,000 m^3/day. The RO and MED combination produced 250,000 m^3/day. Therefore, RO combined with MED is the best option [43]. Garcia et al. [31] modeled an

NHES of PV solar power and an SMR in northeastern Arizona. It is demonstrated that the NHES can easily and quickly load follow while having enough energy for an RO plant to function between 15 and 45 MW_e. This amount of energy can produce between 22,425 and 56,377 m^3/hr of fresh water from brackish water found in an aquifer in northeastern Arizona. All of these studies indicate NPP use for desalination can produce large amounts of fresh water and the best option is RO desalination.

When considering costs, current studies show that a large portion of the cost comes from the purchase of oil and fuels. Mabrouk and Fath [44] investigated an integrated thermal MSF-MED desalination technology. In this design, they used both thermal desalination techniques to improve energy efficiency and costs. Cost due to oil prices could be mitigated by using NHES similar to an HTGR desalination plant proposed in an INL report. The benefit of this idea is reducing the CO_2 produced from traditional desalination methods and possibly the cost [30].

Several different types of desalination techniques were investigated to estimate the cost of fresh water when produced with NHES or NPP. One study used the desalination economic evaluation program (DEEP) developed by the International Atomic Energy Agency (IAEA) to determine economic and technical calculations for SMRs in the Middle East and North Africa. It was determined it is both technologically and economically viable option for these states. The most cost effective option in this analysis was the RO operation, \$0.81/m^3 for a plant output of 40,000 m^3/day [45]. Alonso et al. [46] considered two reactors, the AP1000 and IRIS, for desalination in the northwestern region of Mexico. Both produced large amounts of fresh water if combined with any desalination technique. As with the other studies, RO was the most cost effective with \$0.53/m^3 and \$0.55/m^3 for the AP1000 and the IRIS, respectively. Because the AP1000 is a large reactor more water is created by it than the IRIS but all values are comparable for the cost of water. Misra [47] estimated the cost of making 6.935 million cubic meters of water by combining an HTGR and thermal desalination would cost about \$0.45/m^3. Which is more expensive than the fossil fuel case at the current cost of fossil fuels. In order for nuclear desalination combination to become more cost-competitive, fossil fuel prices must become much higher.

From the literature the main concern for nuclear desalination is not if NHES can be used for desalination purposes, but what is the best desalination method to use with the NHES. That is the reason the ECL is considered for experimentation with desalination techniques; lab scale experiments can be run with the system to test the effectiveness of the technique.

2.3.4 Biofuel production via fast pyrolysis

Another use of process heat from an NPP or NHES is the production of biofuels and byproducts associated with the treatment of biomass. The two main products include ethanol and hydrocarbon fuels. There is limited research on the specific combination of nuclear and biomass uses; almost all of which can be found in Forsberg's body of work [5, 6, 9, 48–50]. This idea is also briefly mentioned in two conference proceedings [2, 3]. Most studies only discuss the idea of NHES use in biomass treatments not the technical design, modeling, or experimentation of the technology.

In a review by Farrell et al. [51] different types of processes used for creating energy from biomass were presented. The goals for biofuel research are to find a low-cost option that uses little water, land, and no food crops while producing high-energy liquid fuels. Wastes and otherwise unusable biomass are desirable inputs. These types of materials are high in lignocellulose, a large and highly branched, molecule that is a combination of lignin and cellulose. Wood and residue crops, like corn stover, are rich in lignocellulose and are readily available wastes. To treat lignocellulose, fermentation or thermochemical treatments are used. Biofuels are also an attractive, carbon neutral technology. CO_2 is produced when burning the fuels, similar to traditional fossil fuels, however, the biomass used to create the fuels consumes CO_2 to live. It is a cycle that sustains itself with few GHG emissions. The most abundant feedstock for liquid biofuels is crop residues left behind after harvesting. In order to make these fuels worthwhile, the heat, electricity, and hydrogen used to create them must come from a carbon neutral source, such as nuclear. This is the combination Forsberg proposed in his work on biofuels and nuclear energy [9].

This research focuses on the production of hydrocarbon fuels, bio-oils henceforth, from NHES. The hydrocarbon fuels derived from biomass can create more energy and replace more traditional fossil fuels than bioethanol. There are several reasons for this; current ethanol production largely uses crops that are also food for people to create bioethanol, lignocellulose is difficult to deal with when making ethanol, and the usable energy from the ethanol is only 50% of the original energy value in the original biomass [9]. Bio-oil is a much more desirable product and has higher energy values compared to ethanol [5]. Turning biomass into bio-oil also allows for more of the carbon content to be turned into fuel, including the lignocellulose [50]. There is promising use for NHES and bioethanol production but is outside of the scope of this research for the reasons above [48].

Thermal treatments of biomass for energy products include combustion, gasification, and pyrolysis. Of all these processes pyrolysis can create high liquid yields with moderate temperatures [51]. Pyrolysis is using heat to decompose a substance in an oxygen free environment [52]. Pyrolysis of biomass can be done with slow pyrolysis or fast pyrolysis. Slow pyrolysis produces almost even amounts of gas, solid char, and liquids; while fast pyrolysis drastically changes the outcome and creates mostly liquid products [51, 53]. Ideal fast pyrolysis conditions are near 500°C and the particle residency time is less than two seconds inside the heating vessel [51–54]. From the literature, there are three large areas of study for pyrolysis; the biomass feedstocks, reactors modeling and design, and upgrading the bio-oil for practical use. The following sections will look closer into these categories.

The biomass used in fast pyrolysis can be many things. In one review almost 100 different types of biomass were analyzed. Many were wood types and some were crop residues; all of which were able to produce bio-oil [55]. This review is far too large to go into great detail here, but illustrates the amount of research that has been completed on biomass as well as how diverse the use of pyrolysis is. Steele et al. [56] studied the production and use of bio-oil made from whole southern pine for creation of heating fuel. When compared to regular fuel oil the CO_2 emissions were reduced by 70% in the creation of bio-oil. Total energy consumption was much less for the bio-oil than traditional fuel oil as well, pyrolysis oil proved to be a carbon neutral way of creating and using heating fuel. Crop residues and wood wastes are not the only feedstocks being used. *Lemna minor* or duckweed was used in one study. The reason for using duckweed is, it is a quickly growing aquatic plant that can be harvested often and the worry of running out of the biomass is not a concern. The results showed the duckweed can be pyrolyzed at 500°C and produce 40 wt% bio-oil [57]. Similar results were found by Liu et al. [58] however the maximum yield of hydrocarbons was at 750°C, much higher than the previous study. Several other studies used manure as the biomass source, but these focused on the production of char rather than production of liquid fuel [59, 60]. The possibilities for feedstocks are very diverse, making pyrolysis more attractive when dealing with wastes and creating useful products.

An equally important part of the pyrolysis system is the type of pyrolysis reactor used. The most commonly used reactor is a fluidized bed reactor (FBR). A gas is pumped through the heated reactor which causes a heating medium, such as sand, to act as a fluid and heat biomass particles quickly [61]. One of the simplest reactors used is a bubbling fluidized bed reactor. This is compared to other reactor types and considered very useful for biomass pyrolysis in a review by Bridgewater [62]. Wang et al. [63] modeled and verified the use of an FBR for pyrolysis of pine, beech, bamboo, and demolition wood. The pine and beech wood had the highest bio-oil yield at about 65 wt%, while the remaining two had much higher char production. The traditional fast pyrolysis condition of 500°C and less than two seconds particle retention time were proved to be optimal for the liquid production. In a model created by Xue et al. [64], similar results were obtained with 76% bio-oil creation in the FBR. FBR are useful and well tested reactors for pyrolysis bio-oil production.

The next challenge concerning pyrolysis for hydrocarbon rich fuel is how to upgrade the bio-oil to be used as a fossil fuel replacement. The three major types of upgrading are hydrodeoxygenation, zeolite upgrading, and steam reforming. By using heat and pressurized hydrogen with a catalyst the amount of oxygenated compounds in the bio-oil can be lowered to a level closer to that of diesel or gasoline, this is hydrodeoxygenation [54]. This is done by breaking the bonds. By adding a catalyst CO_2 or H_2O are produced during the breaking of carbon-oxygen bonds. This is called catalytic cracking [65]. As pointed out in a study done my Steele et al. [66], bio-oil is very high in oxygenated compounds. The use of a nickel catalyst and the high pressure hydrogen showed good stability and the product was very similar to gasoline and diesel. They also tested the miscibility of the bio-oil in gasoline and diesel and the mixture remained stable over a long period of time, a major concern with bio-oil and found it comparable to normal gasoline and diesel.

The second method using zeolite upgrading is similar to the hydrodeoxygenation but without the pressurized hydrogen. Zeolites are porous materials of different chemical compositions and are able to create aromatic compounds from highly oxygenated compounds [65]. Imran et al. [67] studied the use of different acidic zeolites, H-Y and H-ZSM5, for the selectivity of hydrocarbons, phenols, furans, and alcohols from bio-oil. They found the zeolites were better at forming the desired compounds than thermal treatments of the oil and that the higher the acidity of the zeolite, the better the results. Li et al. [68] used pretreatment methods as well as heavy metal modified HZSM-5 zeolite. The results showed that an HCl pretreatment increased the hydrocarbon yield to 54% and the use of iron or zirconium up to 45%. Widayatno et al. [69] had very similar results by using copper on a β zeolite. In the review by Dickerson and Soria [65], over 25 catalysts, zeolite combinations, and experiments were reviewed for just bio-oil production. As the literature shows, a large effort is being put into finding the best combination of catalysts or zeolites for the best reforming of bio-oil.

Thirdly, steam reforming of the bio-oil is used to create hydrogen. Long term storage of bio-oil is a current problem. It is very acidic and volatile, meaning it is corrosive and can change over time [70]. Steam reforming is the treatment of the bio-oil to convert it to a more stable compound. Steam reforming exposes hydrocarbons to high-temperature steam and converts to CO and H_2. The products are either taken as the hydrogen produced or turned to syngas [70–72]. The process often is done over a catalyst to increase the efficiency and hydrogen output [71, 72]. Hydrogen is an extremely marketable product and could make bio-oil an economically competitive commodity.

There is clearly a large body of work on the many aspects of bio-oil and fast pyrolysis. Pyrolysis has challenges like any energy producer. Bio-oil decomposes easily, does not function as well as diesel or gasoline, and does not have a consistent method for production. All of these issues are currently being addressed with studies like those previously mentioned. Another challenge of pyrolysis is where do the heat and energy needed to execute the process come from? As proposed by Forsberg [8] the heat and energy can come from an NHES. Normally the heat comes from burning char and recycling gases produced during the pyrolysis process [52]. The char is burned similar to charcoal and the heat is recycled back in the system. If NHES are used instead, the char can be used for other purposes other than burning for energy, such as soil remediation, heavy metal contamination clean up, or co-firing in coal plants [59, 60, 73, 74]. The bio-oil can be used to replace gasoline or diesel, and wastes can be used for a practical purpose rather than simply being discarded.

CHAPTER 3

Energy Conversion Loop Design and Early Analysis

3.1 Purpose of energy conversion loop

The system designed to mimic the heat from an NPP is called the ECL. This is a piping system made up of many components that allow for preliminary testing of ways to harness process heat for useful purposes. The initial design does not have any capabilities to perform laboratory testing with any of the proposed process heat applications. However, by creating a functioning early design the system can be made less costly and allows for the process heat applications to be determined once the pressure, flow, and temperature conditions are known. Problems that arise with the system itself can be mitigated before more complicated experiments are performed. To better understand how the ECL works, it is necessary to look at the overall design and purpose of each component. An air and water loop make up the whole ECL. Figure 3.1 is a simplified version of the piping and instrumentation diagram (P&ID) and shows the flow and setup of each loop- air loop is shown in red and water loop in blue. In appendix A the complete P&ID can be found.

3.2 Air loop

The most important part of the air loop is the air heater. The red circle at the top of the P&ID represents the heat from an NPP as the air heater. Air is supplied by an air compressor that forces air into a storage tank then to the heater. Temperatures coming from the heater are capped at 426°C; which is the highest temperature the stainless steel 316 piping can withstand safely. When comparing the output to what temperatures exit a real nuclear reactor, this is a very reasonable number. Table 3.1 contains examples of current and proposed NPP and their associated outlet temperatures. Several types of reactors produce temperatures in the range that the air heater provides. Therefore, the ECL can accurately create the temperatures that an NPP produces.

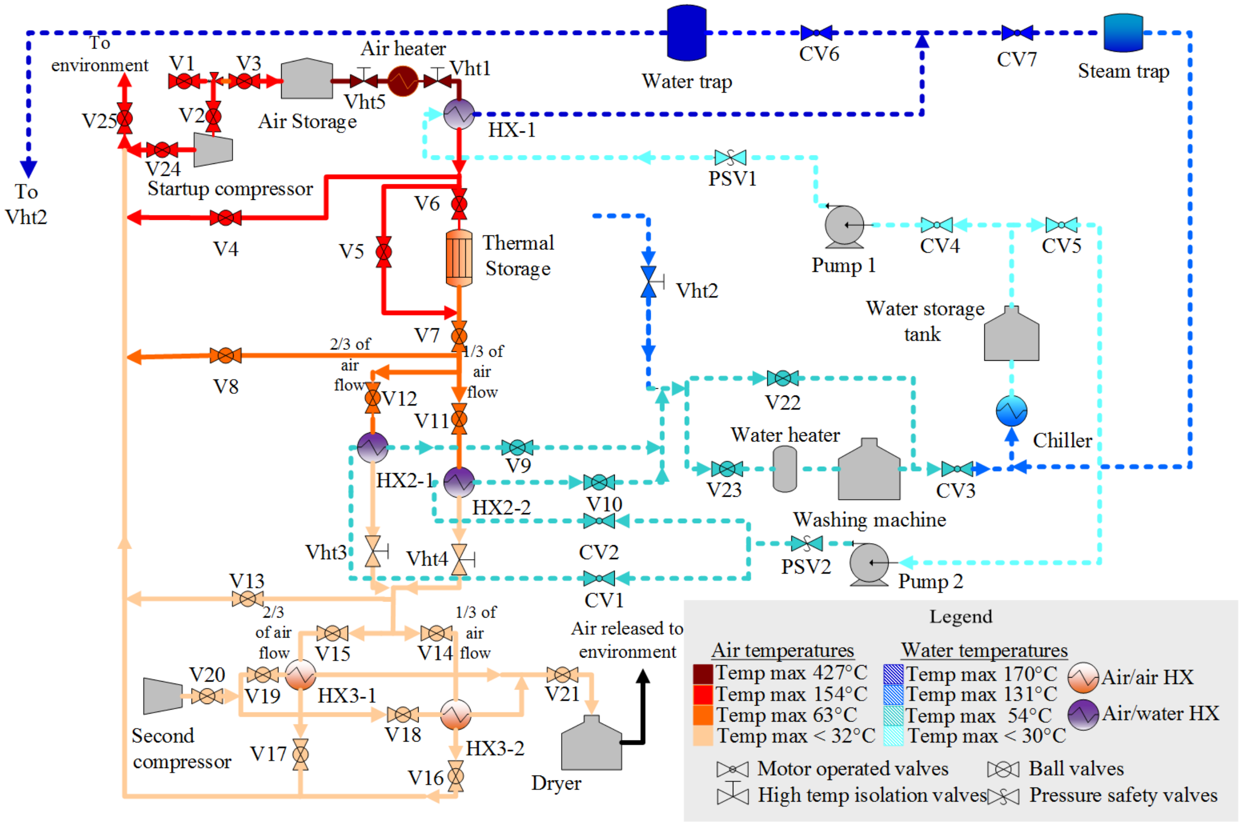


Figure 3.1: Simplified energy conversion loop P&ID

As figure 3.2 further illustrates, the air flows from the compressor to the heater. From the heater, the air flows to the first of five heat exchangers. This is a parallel flow, shell and tube heat exchanger; air flows through the shell side of heat exchanger one (HX-1). Water flows through the tube side of HX-1 and will be discussed later. The air can flow to three different paths; back to the air storage, to a thermal energy storage (TES) device, or bypass the TES to the next set of heat exchangers. The TES tests the ability of the system to experiment with thermal energy storage technology and can be filled with any medium to test the ability to store heat effectively. Thermal energy storage is storing energy in the form of heat. It can be used later to enhance another heat source or smooth out energy production from other sources [2].

If the TES is bypassed the air flows to two air and water heat exchangers (HX2-1, HX2-2). These heat water for use in the water loop side of the ECL. After these two heat exchangers

Table 3.1: Reactor outlet temperatures

Reactor types	Outlet temperature (°C)
Operating reactors [75]	
pressurized water reactor (PWR)	325
boiling water reactor (BWR)	290
pressurized heavy-water reactor (PHWR)	290
Proposed small modular reactors [2]	
light water reactors (LWR)	285-330
heavy water reactors (HWR)	285-310
gas cooled reactors (GCR)	750-900
liquid metal cooled reactors (LMCR)	485-550

are two more heat exchangers. These are air to air heat exchangers (HX3-1, HX3-2), which heat the air from a second compressor used in the dryer seen on the bottom center of the P&ID. After the HX3's the air flows back to the air storage tank and the flow starts over. Figure 3.2 shows the entire flow of air through the system and what it will look like in a realistic setting.

3.3 Water loop

The water side of the system begins at the water storage tank on the right-hand side of the P&ID or in figure 3.3. From the storage tank, the water is pumped by pump one or two. Pump one sends water to HX-1 and the water is heated by the air from the heater. After being heated the water flows either to a steam trap or water trap. The steam trap will send the water to the chiller and back to the water tank. If the water trap is used the steam will be sent to the water heater and used by the washing machine, or it can bypass these and flow back in the chiller. Pump two sends water flows to HX2-1 and HX2-2 to be heated, but only to moderate temperatures not turned to steam. This water is used in the water heater and washing machine or is sent to the chiller. Full models of the combined loops can be found in figures 3.4 and 3.5.

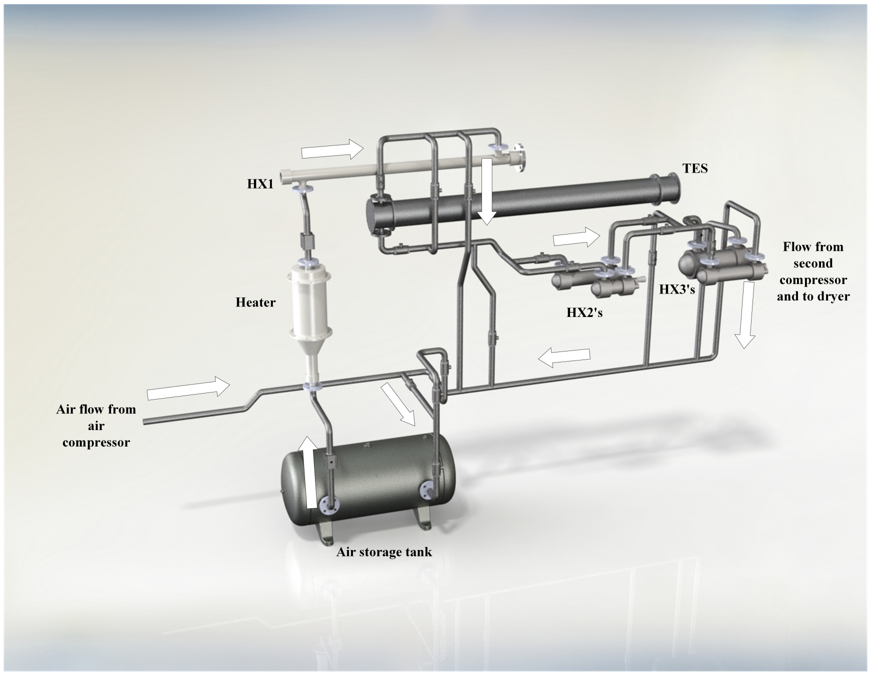


Figure 3.2: Air loop configuration

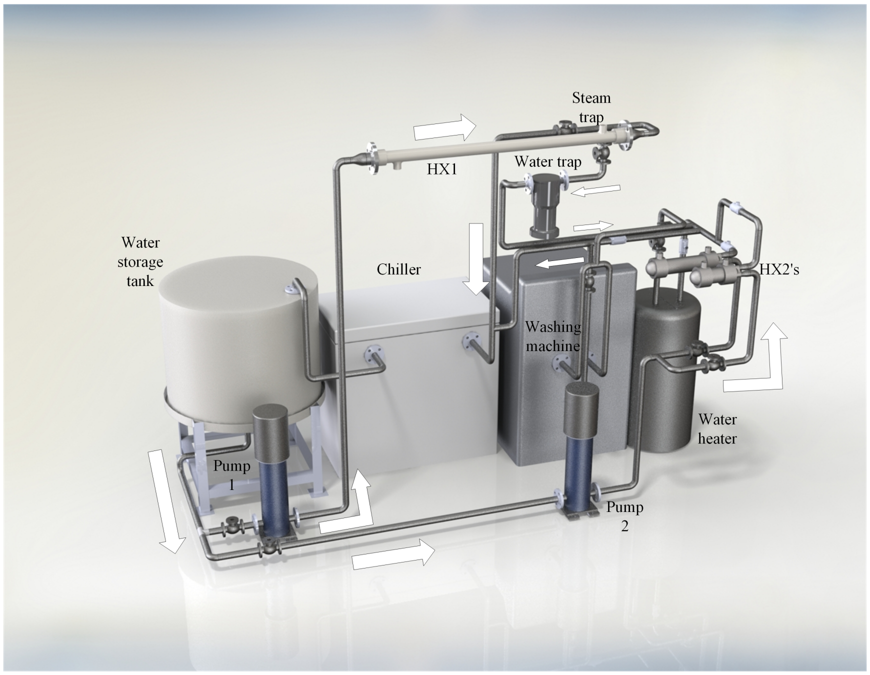


Figure 3.3: Water loop configuration

Figure 3.4: Front ECL Solidworks model

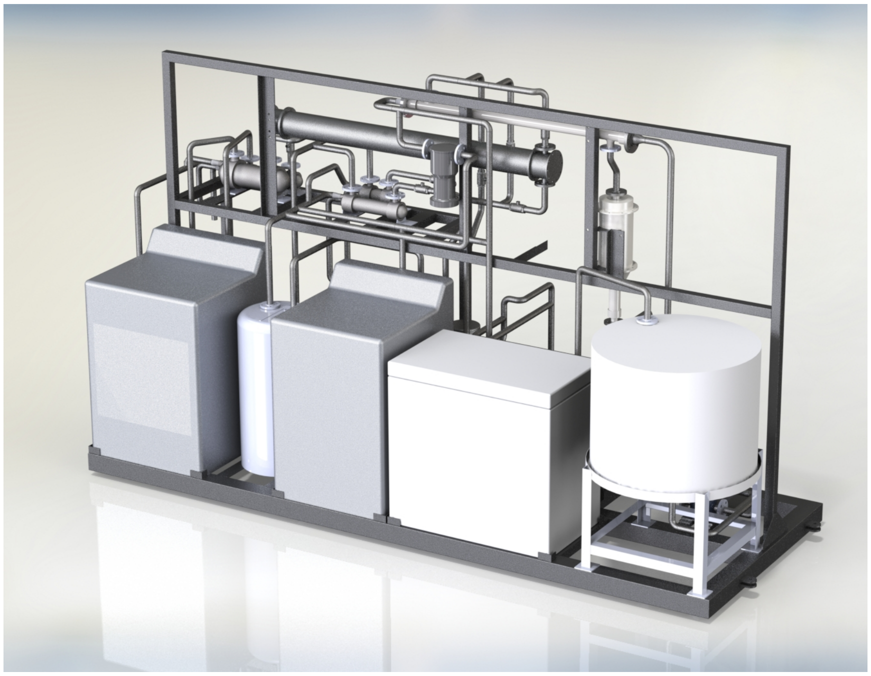


Figure 3.5: Back ECL Solidworks model

3.4 Apparatus of ECL

The clothing washing machine and dryer on the ECL are used as a testbed to determine the functionality of the system. A washer and dryer are two devices that need hot air or water and are used as thermal loads. If the system works with these two machines then the water and air are able to be used with more complex systems. Depending on the conditions at the sections of the piping system experiments can be physically coupled in to use the air or water. Each apparatus on the ECL is testing what possible experiments can be run at those locations. The following section will explore the engineering analysis of the ECL for the design of future experiments.

3.5 Engineering analysis

The system was modeled in Aspen HYSYS [76] and can be found in appendix B.1. From the modeling results; temperatures, flows, and pressures guide the specifications of the system. Below in table 3.2 the temperatures and pressures at key points in the system are presented.

Table 3.2: HYSYS temperatures and pressures

Heat exchanger		Operating Temp (°C)		Max Pressure (Pa x10 ^{3})	
		In	Out	In	Out
HX1	Air	426.6	154.8	675.9	662.4
	Water	30.1	170	689.5	675.7
HX2s	Air	154.8	55.1	662.4	649.2
	Water	30.1	36.1	689.5	675.7
HX3s	Air	55.1	47.3	649.2	636.2
	Air	25.0	49.4	172.3	168.9
To washing machine		51.7		275.8	
To dryer		49.4		168.9	
To chiller		30.0		270.3	

Based on previous research, sections of the ECL will coincide best with certain experimental operations.Thermal desalination techniques, MED and MFS, would be appropriate to test with the ECL. MED uses temperatures near 71.2°C and MFS uses 90-110°C [77].

Both of these technologies and conditions would be easily produced by the ECL from the model results. If electrical production were accomplished in later research of the ECL RO technology could also be considered. Hydrogen production is unlikely to be tested with the ECL due to the need of temperatures around 900°C (1652°F) [37]. Similar to desalination, if electricity were produced, electrolysis may be a possibility. Lastly, pyrolysis would work with the system. The highest temperature needed to make bio-oil is 500°C; lower temperatures can be used to create char and lower amounts of oil [52, 55, 78]. In figures 3.6 to 3.8 the technologies are illustrated and show how the system works and where the ECL will be incorporated.

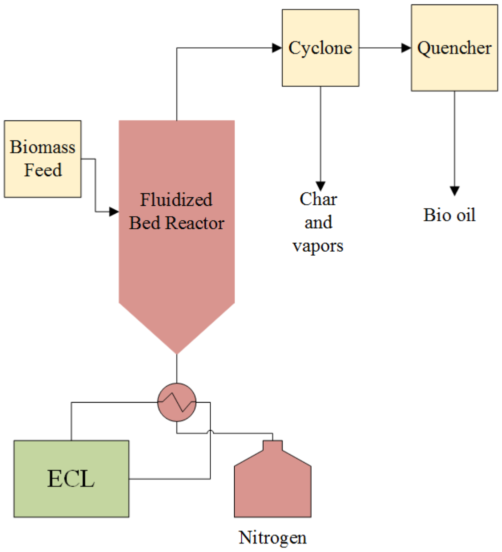


Figure 3.6: Fludized bed pyrolysis reactor [79]

Figure 3.6 illustrates how the ECL would be attached to an FBR for pyrolysis experimentation in the future. The ECL heats the nitrogen, or other inert gas, that flows into the FBR and fluidizes the sand that exchanges heat with the biomass particles. A heat exchanger would have to be used to heat the nitrogen and the air or steam would not be used directly in the pyrolysis apparatus.

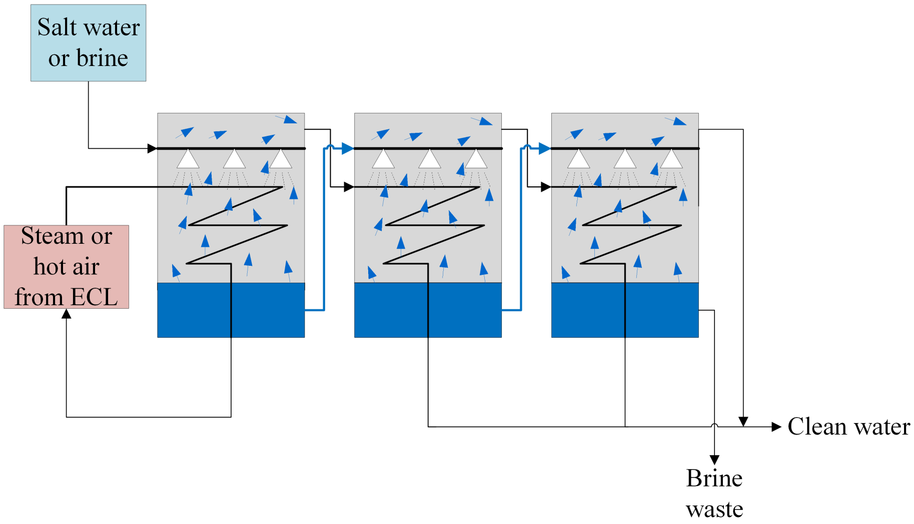


Figure 3.7: Multi-effect desalination [77]

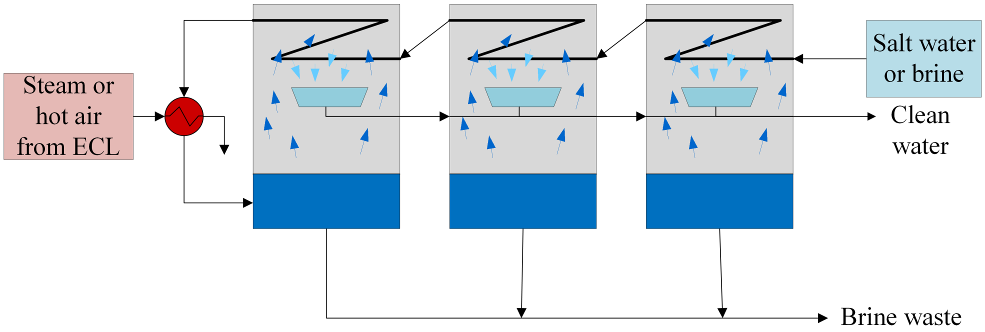


Figure 3.8: Multi-stage flash distillation [77]

Figures 3.7 and 3.8 show the two types of thermal desalination that could be added into the ECL. MSF distillation requires a heat exchanger to be placed in the system similar to the FBR pyrolysis unit. MED distillation could have the piping in the ECL run through the first effect and begin the distillation cycle. From the literature review, a MED unit is most attractive for future testing; reasons include appropriate temperatures for the ECL [41], use with geothermal technology very similar to steam from an NPP [42], possible pairing with NuScale's SMR and RO was the most efficient in one study [43], and combined MFS-MED technology proved to be the most economical and efficient [44].

To give an overview of where the different tests could exist in the ECL, figure 3.9 shows these locations on the P&ID. Pyrolysis will work after the heater or after HX-1 because of the high temperatures required for the process. Thermal desalination could be used at multiple points because of the lower temperature requirements. The capability of producing electricity with the system for use in RO desalination or hydrogen production could be explored in the future but is outside the scope of the current research. However, electricity production would be most able to occur at the section indicated in figure 3.9.

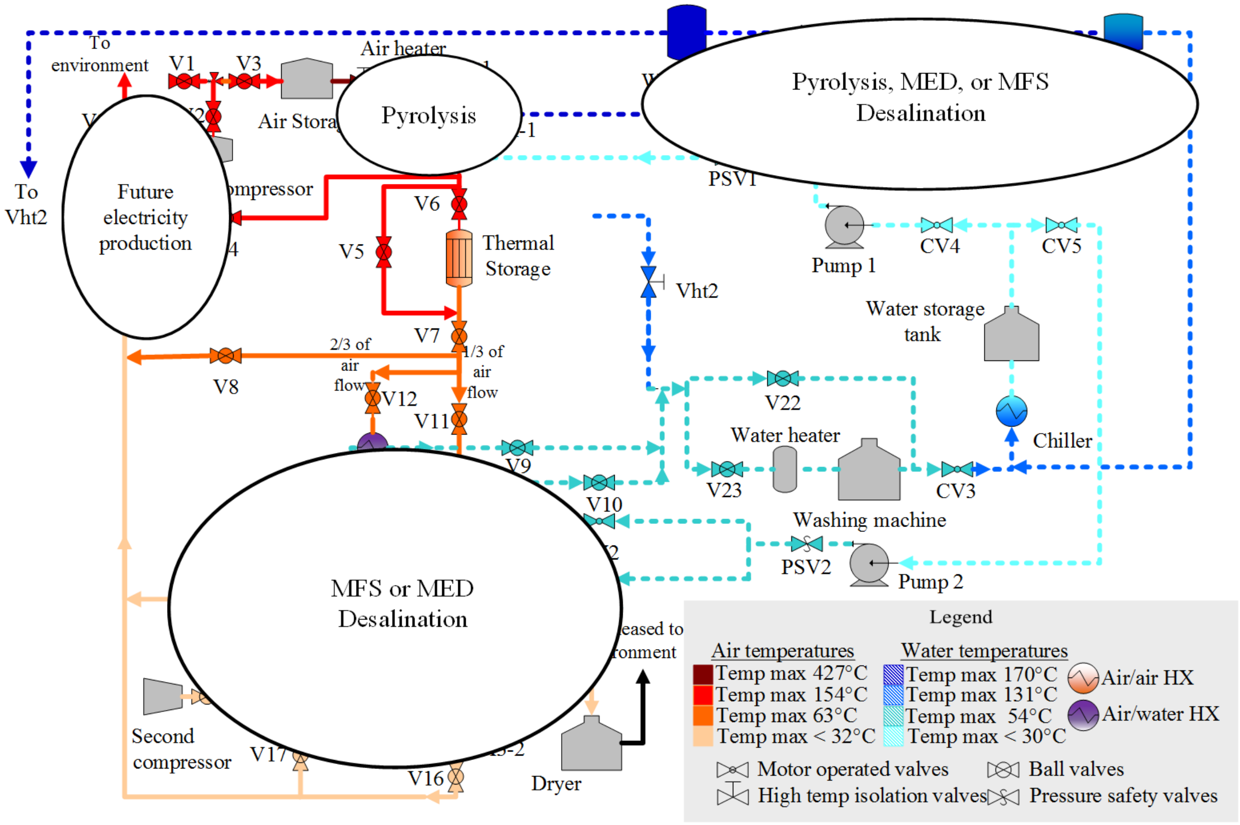


Figure 3.9: P&ID placement of future experiments

CHAPTER 4

Experimental Design

4.1 Developing the experimental procedures

The Aspen HYSYS model was created by Jivan Kahtry, a Ph.D. student at the University of Idaho, and Dr. Michael McKellar of the INL. Over the course of this project, many models were completed and many modifications were made to the ECL design. The results presented in table 3.2 are the most simplified, yet the most similar to how the ECL currently exists. The Aspen HYSYS model results were used to calculate what conditions are required by the components in the system. All components, excluding the air compressor, were recycled from another project or purchased early on in the process before my involvement. The components of the system were appropriate for the desired experimental conditions based on the Aspen HYSYS modeling results. By using the manufacturer's specifications it was found that each component was able to operate under the necessary temperature, pressure, and flow. From the values and component designs from the Aspen HYSYS model and manufacturer's specifications from the previously purchased equipment, the ECL SolidWorks model was created. The SolidWorks model allowed us to see the flow of the air and water throughout the system. It was imperative that the air and water flowed easily throughout the system, in order to design experiments and understanding the ECL. The SolidWorks models showed the flow of the different substances and if there were any problematic portions of the system. The Aspen HYSYS values were also used in the SolidWorks models to determine flow in the individual experimental procedures at different pressures and temperatures. Based on these results the physical experiments were planned and conducted. Selected SolidWorks flow models are shown in the next section. The full SolidWorks model can be found in appendix B in figures 3.4 and 3.5.

4.2 ECL experimental procedures

A series of procedures instruct how each part of the system can be tested and how to start and shutdown the ECL in ideal conditions. The five procedures are;

- Hybrid energy conversion loop start-up procedure
- Thermal energy storage experimental plan
- Washing machine and water loop experimental procedure
- Hybrid energy conversion loop dryer test procedure
- Hybrid energy conversion loop shutdown procedure

Full procedures can be found in appendix C, D, and E. The start-up plan initializes the air flow and water flows into the system and also allows for the heater to raise to the desired 426.6°C safely. Once the system reaches steady state any of the three systems; washer, dryer, or TES, can be tested. Below is a model (figure 4.1) of how the water will flow from the water storage tank into the washing machine for testing.

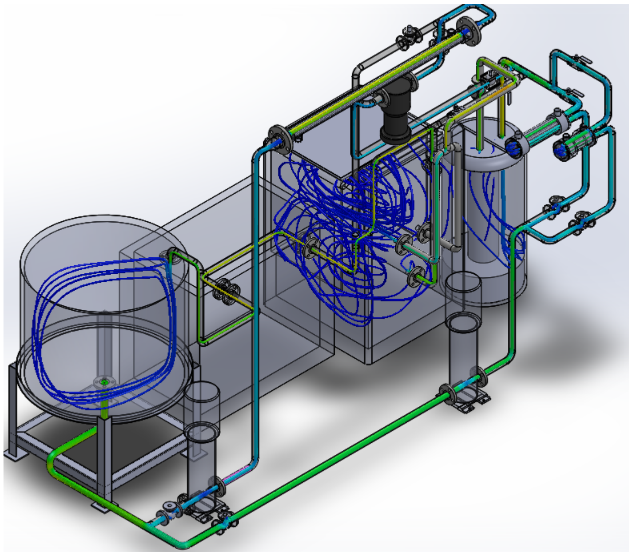


Figure 4.1: Complete flow of washing machine experiment

This will be the final stage of the procedure with all previous steps working towards this state. The air loop will be running as explained by the start-up procedure (figure 4.2).

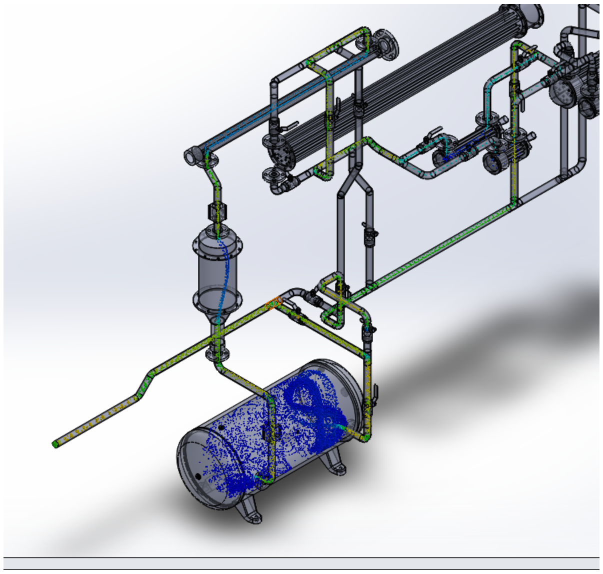


Figure 4.2: Air flow during washing machine testing

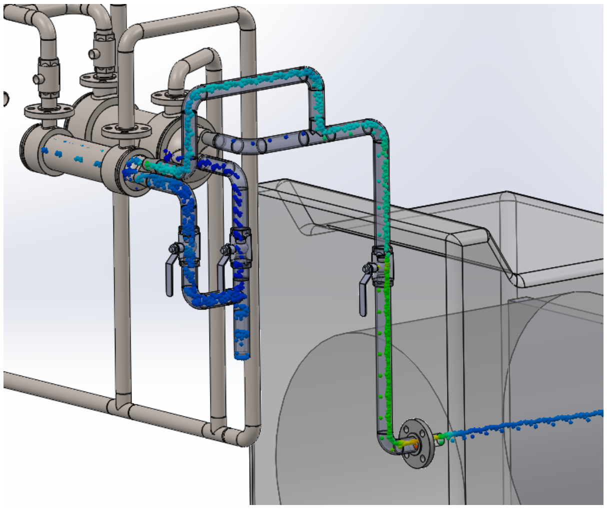


Figure 4.3: Air flow into dryer

Another option is to test the dryer to see the usability of the heated air. This can be seen in figure 4.3. The air flows from the second air compressor through the HX3-1 and HX3-2 where it is heated by the air flowing through the opposite side from the heater then is used by the dryer. The TES procedure will be overlooked for this experiment due to time and material limitations.

All of the experimental procedures are based on of the SolidWorks and Aspen HYSYS models under ideal conditions. The experimental procedures are included in this document to illustrate the possible experiments that can be run with the ECL. Simple tests were run with the ECL as explained in chapter 5 before full experiments occurred.

4.3 Pyrolysis experimental design

4.3.1 Feedstock

As previously mentioned many materials can be used for biomass pyrolysis; manure [59,60], duckweed [57,58], or woods such as pine [63]. Mohan et al. [55] showed that biomass feedstock can come from numerous processes, specifically agricultural or forest industries. Common forms are straw, corn stover, wood wastes, and grasses. These are all materials that are abundant and easily obtained, a desirable quality when considering what type of biomass to use in bio-oil production. Biomass with low water content is desirable to increase the energy efficiency and the quality of the product [55]. For the purposes of this research, corn stover will be used as the biomass feedstock. Corn stover is the waste left after harvesting corn; like the stalk, cobs, husk, or leaves. It is an abundant biomass source, 94.6 million dry tons a year are available in the United States, and do not compete with land for food production [80].

The biomass feedstock was provided by the INL and was collected from Boone County, Iowa in 2011. The biomass was characterized by the INL and the values of characterization can be found in the appendix F. The proximate and ultimate analysis are shown. Ultimate analysis of biomass shows the chemical components, while proximate analysis shows the structural components [81]. The ultimate analysis includes the percent of hydrogen, carbon, and nitrogen. Biomass sources have higher oxygen content than coal and traditional fuels, correlating to a higher O/C ratio. This high ratio indicates low high heating values (HHV) for the fuel [82]. The proximate analysis includes percent volatile matter, ash, and fixed carbon [82]. The fixed carbon is another determining factor to the HHV, high fixed carbon means higher HHV [81]. From these values, the corn stover is a plausible feedstock for bio-oil production. It is a waste product, has heating values similar to those of other biomass, and is readily available wherever corn is grown [81–83].

The corn stover was ground in an electric coffee grinder to make the material finer. After this, it was filtered through a sieve with two layers of mesh and weighed into 0.50 gram samples. Based on the mesh size, the samples are approximately 20 micrometers sized.

4.3.2 Distillation setup

While designing the pyrolysis experiment, the following information is pivotal in how to complete the distillation setup and testing. There are two main pathways of kinetic mechanisms pyrolysis products will take. One is depolymerization reactions, the other is dehydration reactions. Dehydration creates char, CO_2, and water and occurs at lower temperatures. Depolymerization reactions create vapor containing desirable species and degradation products. By allowing the vapors to rapidly leave the container the oils and tar will condense; if they stay in the container further char, gases, and water are created [83]. Therefore, by using a small amount of biomass and allowing it to rapidly escape the three-necked flask when vaporized, and condensation can quickly occur without secondary reactions.

For the purposes of this experiment a very simple, small scale distillation setup was used. As a proof of concept, the anticipated temperatures produced by the ECL were created via the heating mantle seen in figure 4.4. The system was flushed with nitrogen as it was heated in order to keep the environment for pyrolysis as oxygen free as possible. Biomass was introduced into the system once it had reached temperature. This was done with the solid addition flask, similar to the one in figure 4.4. To prevent the biomass from burning to the sides of the three-necked flask boiling chips were placed in the bottom to mix the biomass particles and increase the heating surface area. The experiment was heated with a heating mantel with a maximum temperature of 500°C. Once the biomass was pyrolyzed the vapors flowed out of the flask into the condensation column. The column was cooled with a water jacket on the outside. The cooled liquid was collected in the final flask seen at the end of the system. Each test lasted for 10 minutes. After that time the vapors and particles that did not condense were flushed out of the system with nitrogen.

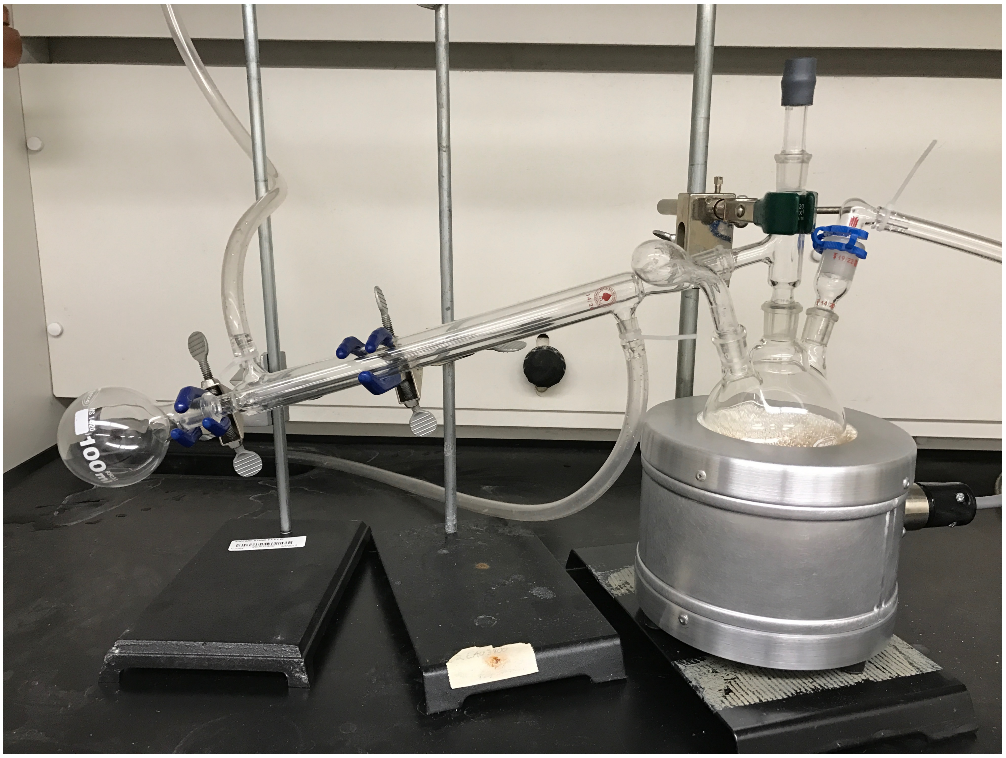


Figure 4.4: Distillation set up

4.3.3 Metrics

Further testing of the bio-oil was saved for a later date. The metrics of bio-oil production were quantitative rather than qualitative. Instead, the amount of oil produced and the amount of residue left from the biomass verified the appropriate temperatures to perform future experiments. This was determined by weight and volume. The weight of the biomass prior to pyrolysis was recorded, the weight left in the three-necked flask, and the volume of the bio-oil was recorded. Based on the literature and past work, the higher the temperature the more bio-oil will be produced. The lower temperatures produce more solid char [52, 55, 78].

CHAPTER 5

Testing and Experimental Results

5.1 Pyrolysis results

Initial experiments used 0.25 grams of biomass. This amount was insufficient and no product resulted from distillation. To increase the amount of product oil, biomass was increased to 0.50 grams. Three tests were run sequentially at one temperature. The first biomass sample was added to the three-necked flask via the solids addition flask and allowed to rest for ten minutes. Nitrogen was purged through the system before adding the next sample at the same temperature. Appendix F has a more detailed description of the exact actions done during the experiments. There was an insufficient amount of bio-oil in the condensation column to collect in every test. To determine the amount of oil produced, the collection flask was weighed before and after testing. A small amount of oil was produced, so it was necessary to account for mass gained in the collection flask, as well as weight loss in the three-necked pyrolysis flask to determine actual oil production. The original biomass sample weights and the flasks weight changes are presented in table 5.1.

Table 5.1: Pyrolysis experimental results

Temperature (°C)	Run A (g)	Run B (g)	Run C (g)	Flask weight difference (g)	Collection weight difference (g)
300	0.47	0.49	0.48	0.22	0.04
325	0.53	0.51	0.51	0.2	0.12
350	0.51	0.51	0.47	0.16	0.01
375	0.50	0.52	0.49	0.13	0.01
400	0.47	0.48	0.48	0.15	0.06
425	0.48	0.50	0.51	0.25	0.01

From table 5.1 the three necked flask weights decrease until the 425°C test. Increased mass loss was attributed to increased biomass devolatilization. This was expected with increasing temperatures. However, the value for the 425°C experiment was attributed to experimental error. This value is neither consistent with the trend of results, nor is it explainable through data in previous pyrolysis work. The weight of the collection flask also measures the amount of condensible vapors collected on the walls of the flask. No liquids were collected during the experiments, but as seen in figure 5.1 a thin film appeared on the collection flask on the left. This is believed to be bio-oil condensate.

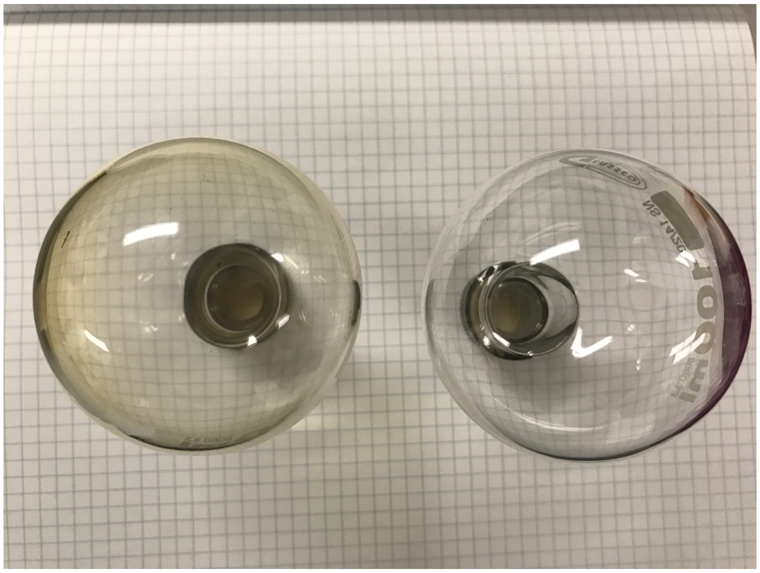


Figure 5.1: Film covering collection flask

At lower temperatures, this film was the only observable product. At higher tempera-tures, liquid condensed in the condenser and began to flow to the collection flask. However, the condenser was too long and the amount of liquid was not able to traverse the distance. This condensate can be seen in figure 5.3. As table 5.1 shows, the weight change of the collection flask decreases as temperature increases. This can be explained by the vapor production and condensation of bio-oil on the three neck adapter (figure 5.2) or the con-denser (figure 5.3), or more complex devolatilization could also be occurring. Meaning, more non-condensible vapors were created at higher temperatures than at the lower temperatures. Those vapors may have evacuated the apparatus with the nitrogen flush.

Figure 5.2: Film coating in three necked adapter

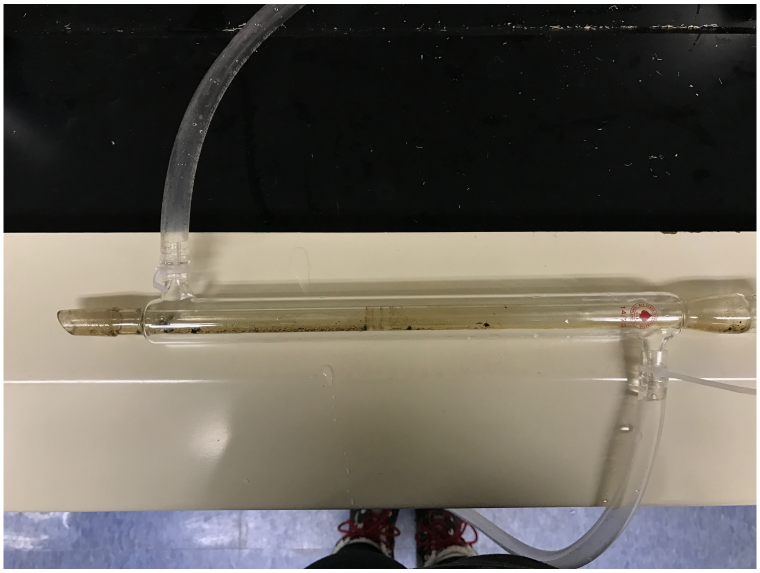


Figure 5.3: Film lining distillation column

5.2 Changes made to the ECL

Testing began with turning on the system and ensuring each component was functional. The air side was tested first, the air compressor was pressurized and slowly air was allowed into the system. Results from pressure sensors, thermocouples, and flow meters were incorrect. It proved that the wiring of these components was incorrect and was rectified. The next problem to solve was the air leakage from the air heater. Huge amounts of air leaked from the bottom of the air heater and allowed no air flow to the rest of the system. To create an area of lower pressure for the air to escape, a pipe was removed at the end of the system. This decreased the air escaping from the heater tremendously, but leakage still occurs. Another concern is the air heater rapidly heats the air and continues to do so after powering down. Because of the leaking air, the compressor quickly decompresses and must be running the entire time with less control. The air flow is not enough to cool the heater in a controlled manner. It was decided by Dr. Ostrom to not exceed 50°C in the heater.

Next, the water storage tank was filled and the components tested. All components were functional and working properly. The only caveat is the pumps cannot be ran simultaneously, there is not enough head pressure currently to allow enough water into the system all at once. The pumps cavitate if running at the same time. The washing machine was also bypassed. This was done to add a heat supply to the system besides the air heater by using the water heater. Because of the safety precautions needed for the air heather the added heat supply helps the system reach higher temperatures overall. The sensors on the water loop were also rewired and are reading correctly.

5.3 ECL testing results

For the purposes of this research, the focus of the experimental analysis will be on the sections of the ECL before and after HX-1. The sections are the most suitable for pyrolysis based on the Aspen HYSYS modeling. A sample of data collected from the test of HX-1 (procedure found in appendix H) is shown in figure 5.3. The output from the water side has a maximum temperature of 26°C, while the output of the air heater reaches nearly 140°C, not shown in this data sample. The flow of the water is so fast there is almost no change in the temperature of the water. The flow of the water is measured only in milliamps and cannot be converted at this time. The flow meters were taken from a previous project and the data sheet giving the conversion of units is not available. Air flow held steady between 17 and 20 kg/hr. To create the heat required in the water loop the air must move much more quickly and the water must slow down. Currently, the water is taking all of the heat from the air and the output of the parallel flowing heater exchanger reaches a pinch point temperature, meaning the temperature output of the air and water are the same.

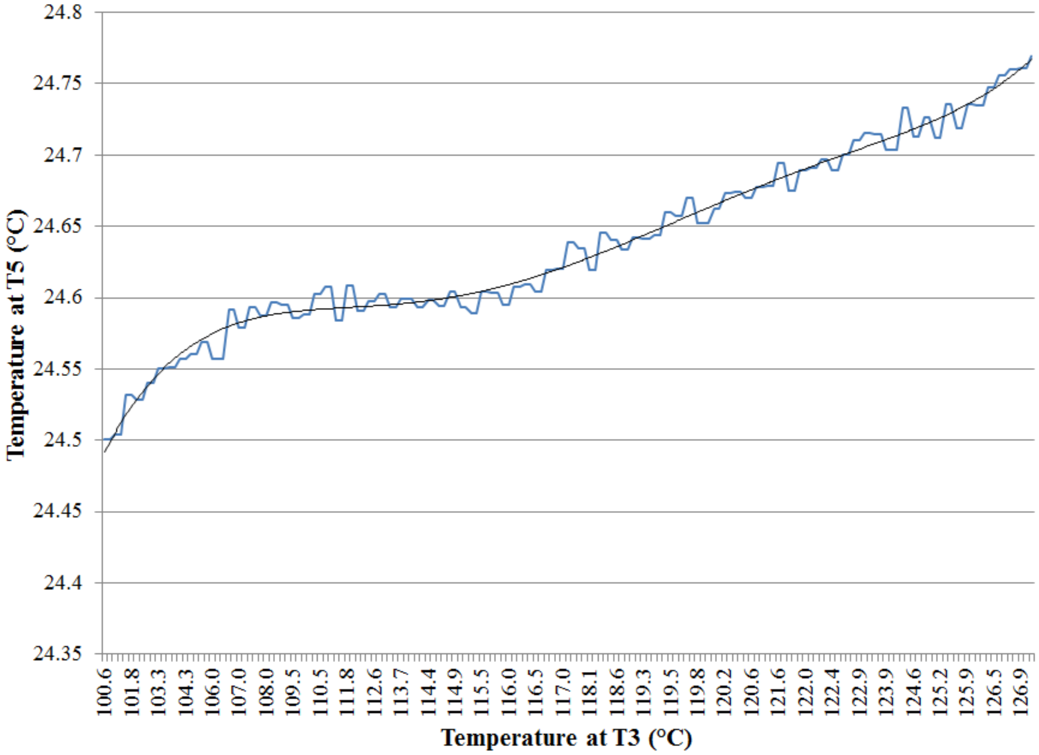


Figure 5.4: Input temperature of air vs. output temperature of water

Using this sample data of 130 data points a regression line is fit to the graph and the following water outlet temperatures presented in table 5.3 are possible. The sample shows a stable increase in temperature that is predictably what would occur when the air temperature increases. Therefore pyrolysis experiments could be performed only at the highest temperature point of the system. The pyrolysis experiment could still take place immediately after the heater if it were replaced with a controllable and safer heater.

Table 5.2: Pyrolysis temperature comparison to HX-1 testing

Pyrolysis temperature (°C)	Water outlet from HX-1 (°C)
300	81.7
325	106.1
350	138.8
375	182.2
400	238.8
425	311.6

5.4 Conclusions

5.4.1 Theoretical vs experimental results

Results from a model are often different than an experimental setup, making physical verification of model results essential. The ECL is a prime example of this. The highest temperature of the Aspen HYSYS model is 426°C and the water temperature heated by this is 274°C. While the highest air temperature can be extrapolated from experimental results to show the water outlet temperature from HX-1 is closer to 312°C. The discrepancies can be described by the difference in equipment used in the model and experiment. The experimental ECL pumps are not controllable like the Aspen HYSYS model is. The flow is different and will affect the outlet temperature of both the air and water loop. The difference between the model and what is achievable with the ECL is highly dependent on the equipment used on the ECL. Several of the components are used from a previous project and are not perfect for the purposes of the ECL. In future work, new equipment needs to be specified and purchased.

5.4.2 Lessons learned

The components used in the ECL were either recycled from a previous project or bought prior to the current modeling and analysis. The cost savings of recycled parts does not outweigh the importance of choosing the parts specifically for their intended purpose. From this, it can be determined the components should be purchased to examine the modeling prediction, or complete the modeling with the specific components in mind. The main problems were the flow of water and air. The pumps are powerful and the flow is much higher than the modeled 10.2 kg/hr. When calculating the flow needed for the air side the compressor can produce the desired flow but does not hold the pressurized air long enough to continue to flow over the air heater for extended periods of time. What the pumps and compressor were capable of did not align with what was modeled. Problems such as these could be avoided in the future by modeling the system then purchasing the parts to be exactly what the model showed or creating the model to fit the exact components.

5.4.3 Future work

Replacing components in the ECL is the priority in the future. The air heater is the primary concern. The heater is extremely powerful and possibly dangerous if the temperatures are allowed to escalate unchecked. Control of the heater is done with the flow of air or the power given to the heater in kilowatts. With the current air and power suppliers, the heat cannot be safely controlled. Complete replacement of the heater is required because of this complication and the fact it leaks air drastically. A heater that is controlled easily with a computer or a physical control is required.

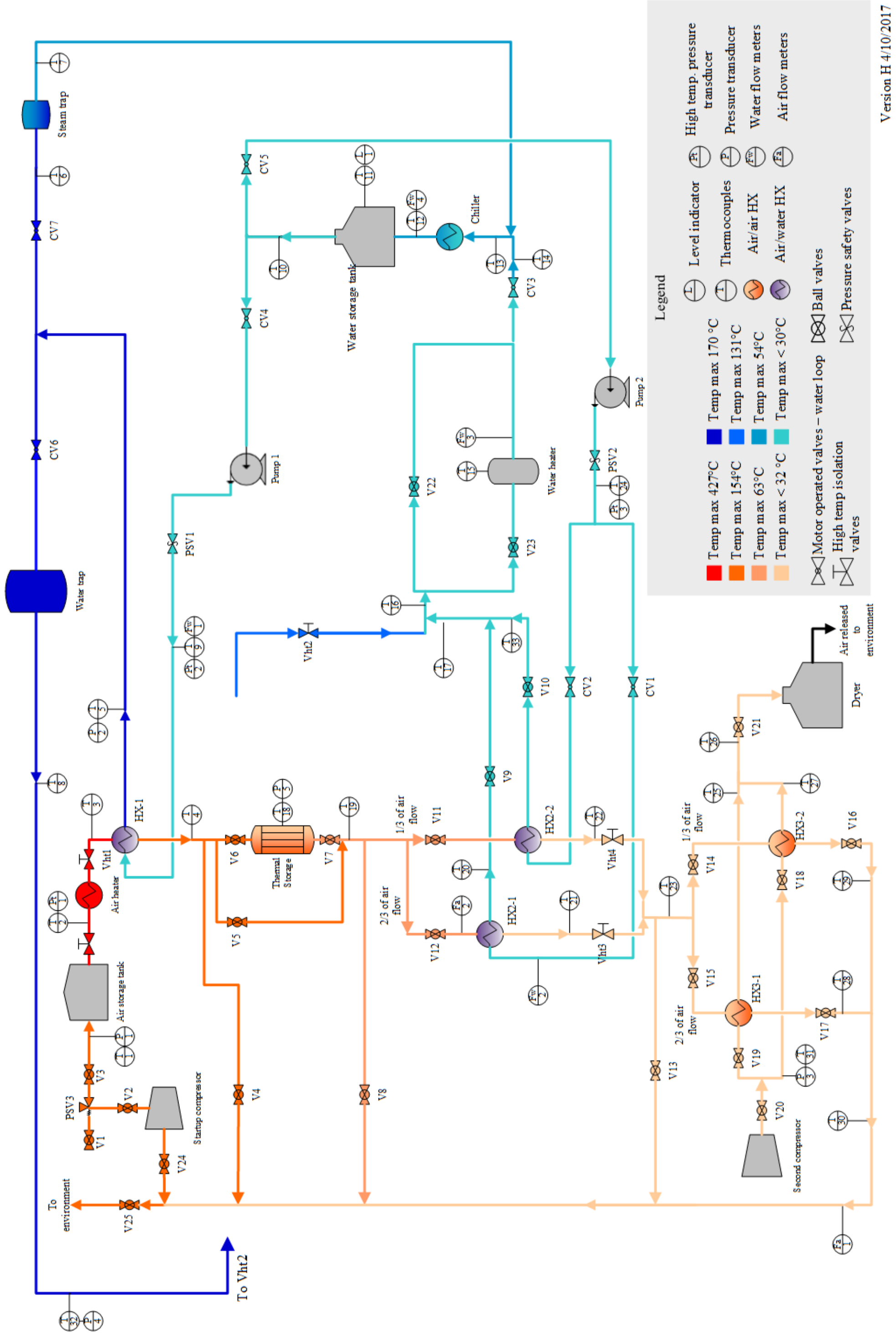
The air supply was not nearly large enough to run a full test of the ECL. A continuous air supply must be connected to the ECL to ensure enough air is received and will flow throughout the system constantly. Flow from the pumps was too fast and did not allow for proper exchanging of heat with the air to the water. This can be mitigated by either replacing the pumps or creating a feedback loop. Splitting the flow of the pump with a tee in the pipe will divert flow to two options. Half the flow will continue to the proper heat exchanger, the other half will divert back to the pump. The water will slow down as well as prevent the pumps from cavitating as they do now.

As for the rest of the system; heat exchangers, flow meters, and valves, all were performing appropriately. HX-1 is far too efficient currently because the flow of the air is not fast enough and the flow of the water is too fast. This is not a problem with the heat exchanger itself and applies to the other four heat exchangers as well. Once the components can be replaced with appropriate parts, the ECL can run full testing of the washer, dryer, and TES. After the modifications more advanced experiments may also be incorporated into the ECL.

APPENDIX A

P&ID

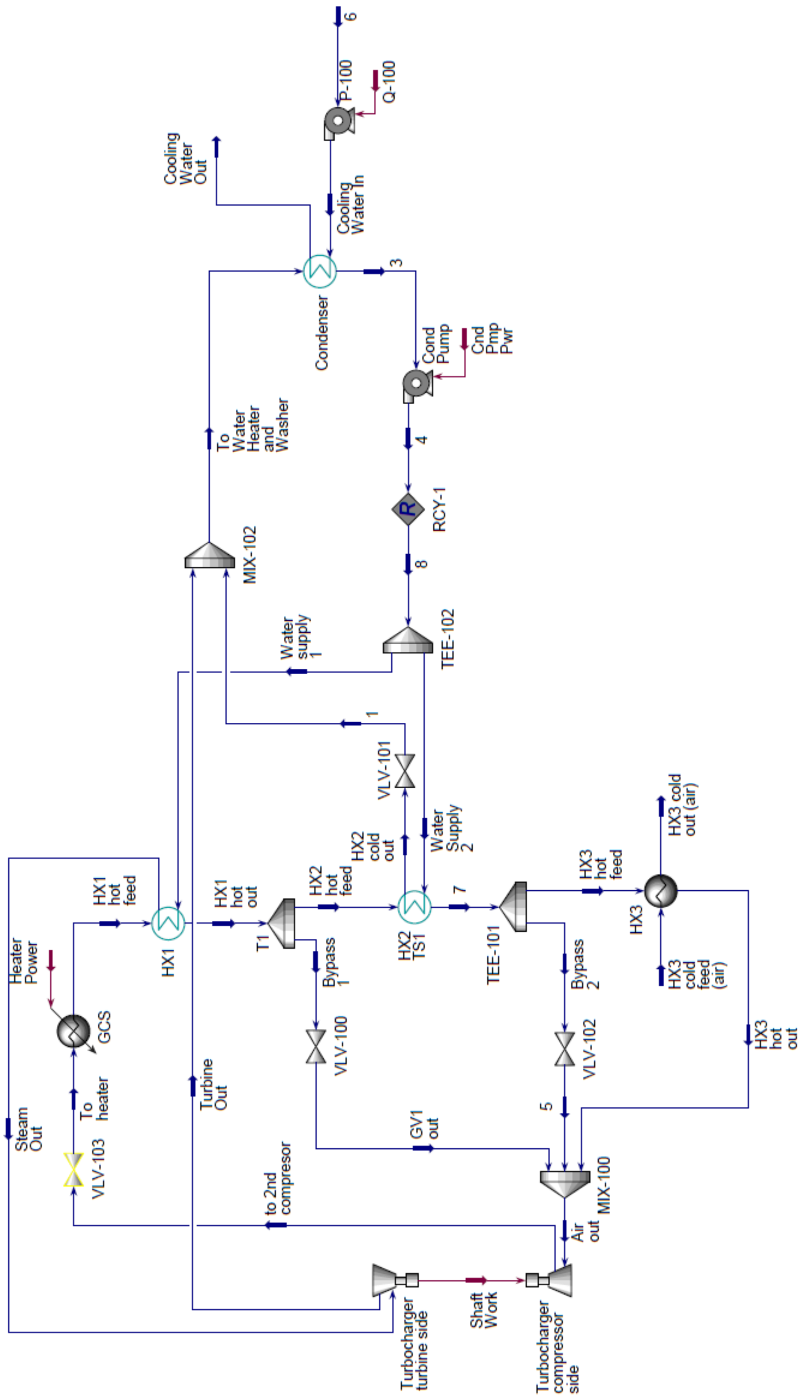
Figure A.1: Complete energy conversion loop P&ID



APPENDIX B

Energy Conversion Loop Aspen HYSYS model

Figure B.1: Aspen HYSYS model



APPENDIX C

Hybrid Energy Conversion Loop Start-up Procedure

Introduction

Purpose

The procedure provides the instructions needed to start the air and water flow cycles in the Hybrid Energy Conversion Loop for the NEUP project.

Scope

This procedure gives the actions only for the beginning of the cycle in the loop system. It shows how to begin heating the air in the air system and circulating it and how to create the water flow. It does not include the instructions needed to run the washing machine or dryer. The thermal storage unit is also not being used in this procedure.

Applicability

This procedure only applies to this specific energy conversion loop design.

Precautions and Limitations

A. Portions of the system closest to the air heater will be insulated but still very hot.

B. The turbocharger is not designed to be used with steam so caution should be taken around this instrument while the system is running.

C. Pressure safety valves can release very hot air or steam to environment if pressure exceeds the design pressure.

Prerequisite Actions

Performance Documents

[1] Obtain a copy of the final piping and instrumentation diagram.

[2] Obtain a copy of the final engineering drawings for reference material.

Special Tools, Equipment, Parts, and Supplies

[1] Protective, heat resistant gloves for closing and opening manual valves.

Field Preparations

[1] Ensure water system has water in the water storage tank and piping.

[2] Proper valves must be open in the water system:

- CV1
- CV2
- CV4
- CV7
- V9
- V10
- V22

[3] Proper valves must be closed in the water system:

- CV3
- CV5
- CV6
- V23
- Vht2

[4] Proper valves must be open in the air system:

- V2
- V3
- V5
- V11
- V12
- V13
- V24
- Vht1
- Vht3
- Vht4
- Vht5

[5] Proper valves must be closed in the air system:

- V1
- V4
- V6

- V7
- V8
- V14
- V15
- V16
- V17
- V25

Initializing Water and Air Flow

Initializing Water Loop

Note: *Cumulative time elapsed includes the time needed to fill water tank and check the valves.*

Step	Description	Estimated time elapsed (minutes)	Cumulative time elapsed (minutes)	Reason
1	Turn on pump 1 to pressurize the system to 100 psi. a) Check flow rate at Fw1 is not exceeding 7.71 kg/hr.	5	15	Flow rate entering HX1 cannot exceed 7.71 kg/hr. Cycles water through part of water loop into water storage.
2	Open CV5.	1	16	Allows water through the ”water heating” loop
3	Open CV3.	1	17	Allows water through the chiller and mixes with water from the steam trap.
4	Turn on pump 2. a) Pressurize water to 30 psi. b) Check Fw2 to ensure flow is below 153.3 kg/hr.	5	22	Provides water to the other half of the water loop. Flow rate entering HX2 cannot exceed 153.3 kg/hr.

Initializing Air Loop

Note: *Steps and cumulative time elapsed are continuations of the water loop initializing and include the time needed to ensure proper valves are open or closed.*

Step	Description	Estimated time elapsed (minutes)	Cumulative time elapsed (minutes)	Reason
6	Wait five minutes for the water flowing through the loop to reach steady state.	10	32	
7	Turn on the startup compressor.	5	37	Fills the air storage tank.
8	Open V16 to allow partial amount of air flow (roughly 30 kg/hr) to enter the system.	2	39	Introduce the air flow into the system gradually.
9	Wait 5 minutes to allow the system to reach steady state.	5	44	
10	Open V17 partially to allow more air flow (roughly 60 kg/hr) into the system.	2	46	Introduce the air flow into the system gradually.
11	Wait 5 minutes to allow the system to reach steady state.	5	51	

12	Open V17 fully to allow full air flow (roughly 90 kg/hr) into the system.	2	53	Introduce the air flow into the system gradually. This step introduces the complete air flow into the system.
13	Wait 5 minutes to allow the system to reach steady state.	5	58	
14	Turn air heater to 0.248 kW. a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	63	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
15	Wait 20 minutes for system to reach steady state.	20	83	
16	Turn air heater to 0.496 kW. a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	88	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
17	Wait 20 minutes for system to reach steady state.	20	108	

18	Turn air heater to 0.744 kW. a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	113	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
19	Wait 20 minutes for system to reach steady state.	20	133	
20	Turn air heater to 0.992 kW. a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	138	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
21	Wait 20 minutes for system to reach steady state.	20	158	
22	Turn air heater to 1.24 kW. a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	163	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
23	Wait 20 minutes for system to reach steady state.	20	183	

24	Turn air heater to 1.488 kW. a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	188	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
25	Wait 20 minutes for system to reach steady state.	20	208	
26	Turn air heater to 1.736 kW. a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	213	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
27	Wait 20 minutes for system to reach steady state.	20	233	
28	Turn air heater to 1.736 kW. a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	238	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
29	Wait 20 minutes for system to reach steady state.	20	258	

30	Turn air heater to 1.989 kW a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	263	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
31	Wait 20 minutes for system to reach steady state.	20	283	
32	Turn air heater to 2.232 kW. a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	288	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
33	Wait 20 minutes for system to reach steady state.	20	308	
34	Turn air heater to 2.48 kW. a) Ensure all temperatures, pressures, and flow rates are acceptable using the sensors.	5	313	Gradually turn up power to air heaters to monitor the temperatures, pressures, and flow rates.
35	Wait 20 minutes for system to reach steady state.	20	323	

APPENDIX D

Hybrid Energy Conversion Loop Dryer Test Procedure

Introduction

Purpose

This procedure gives the instructions needed to run the air loop for operation of the dryer.

Scope

This procedure gives the actions only for the operation of the air loop needed for the dryer after the previous start up procedure or washing machine procedure has been followed. It shows how to begin heating the air in the air system and circulating it to properly heat the air needed in the dryer. It does not include the instructions needed to run the washing machine or dryer. The thermal storage unit is also not being used in this procedure.

Applicability

This procedure only applies to this specific energy conversion loop design.

Precautions and Limitations

A. Portions of the system closest to the air heater will be insulated but still very hot.

B. The turbocharger is not designed to be used with steam so caution should be taken around this instrument while the system is running.

C. Pressure safety valves can release very hot air or steam to environment if pressure exceeds the design pressure.

D. This procedure should occur after the washing machine test procedure.

Prerequisite Actions

Performance Documents

[1] Obtain a copy of the final piping and instrumentation diagram.

[2] Obtain a copy of the final engineering drawings for reference material.

[3] Obtain a copy of the startup and shut down procedures.

[4] Obtain a copy of manufacturer's dryer instructions.

Special Tools, Equipment, Parts, and Supplies

[1] Protective, heat resistant gloves for closing and opening manual valves.

Field Preparations

[1] Proper valves must be open in the water loop:

- CV5
- CV3
- CV1
- CV2
- CV4
- CV7
- V9
- V10

[2] Proper valves must be closed in the water loop:

- CV6
- V23
- Vht2

[3] Proper valves must be open in the air loop:

- V2
- V3
- V5
- V12
- V11
- V13
- V24
- Vht1
- Vht3
- Vht4
- Vht5
- V19
- V16
- V17

[4] Proper valves must be closed in the air loop:

- V1
- V4

- V6
- V7
- V8
- V14
- V15
- V25
- V21
- V18
- V19
- V20

[5] Allow the water loop to run as normal and continue running as the startup procedure instructs.

Running Dryer Test Loop

Initializing Air Compressor Two Loop

Note: *Cumulative time elapsed includes the time needed for startup procedure to occur.*

Step	Description	Estimated time elapsed (minutes)	Cumulative time elapsed (minutes)	Reason
1	Open V20.	2	325	
2	Open V19.	2	327	Allows air to begin flowing to the dryer.
3	Open V21.	2	329	Air flows into dryer.
3	Open V21.	2	329	Air flows into dryer.
4	Turn on second compressor.	3	332	
5	Open V18	2	334	Air flows through both heat exchangers.
6	Wait. While waiting put load in dryer.	5	339	Allows air to be heated by heat exchangers.
7	Open V15.	2	341	Allows hot air to enter HX3-1.

8	Close V13.	2	343	Air is no longer bypassing dryer.
9	Open V14.	2	345	
10	Wait for air from second air compressor to be heated in HW3s.	15	360	
11	Run dryer as manufacturer's instructions detail.	60	420	
12	While dryer is running monitor T25, T26, T27, T31.	60	420	Tells us the temperature of air entering the dryer.
13	Close V18.	2	422	
14	Turn off second compressor.	3	425	
15	Close V21. Leave V19 open.	2	427	Closes air flow to dryer.

APPENDIX E

Washing Machine and Water Loop Experimental Procedure

Introduction

Purpose

The procedure provides the instructions needed to test the abilities of the water loop specifically for use of the hot water in the washing machine.

Scope

This procedure only gives instructions for the washing machine loop. It does not include startup of shutdown instructions. These instructions show how to create the water flow we want to observe. It does not include the directions to running the washing machine. After this procedure has been completed shutdown may commence or further testing procedures, depending on purpose of experiment.

Applicability

This procedure only applies to this specific energy conversion loop design.

Precautions and Limitations

A. Portions of the system closest to the air heater will be insulated but still very hot.

B. The turbocharger is not designed to be used with steam so caution should be taken around this instrument while the system is running.

C. environment if pressure exceeds the design pressure.

D. If the temperature at T5 ever reaches more than 338 F water flow to CV6 and CV7 must be shut down immediately.

Prerequisite Actions

Performance Documents

[1] Obtain a copy of the final piping and instrumentation diagram.

[2] Obtain a copy of the final engineering drawings for reference material.

[3] Obtain a copy of the final startup and shutdown procedures.

Special Tools, Equipment, Parts, and Supplies

[1] Protective, heat resistant gloves for closing and opening manual valves.

Field Preparations

[1] Ensure system is running steadily and no issues are occurring.

[2] Allow the air loop to run as normal and continue running as the startup procedure instructs.

[3] Proper valves must be open in the water loop:

- CV5
- CV3
- CV1
- CV2
- CV4
- CV7
- V9
- V10

[4] Proper valves must be closed in the water loop:

- CV6
- V23
- Vht2

[5] Proper valves must be open in the air loop:

- V2
- V3
- V5
- V12
- V11
- V13
- V24
- Vht1
- Vht3
- Vht4
- Vht5
- V19
- V16
- V17

[6] Proper valves must be closed in the air loop:

- V1
- V4
- V6
- V7
- V8
- V14
- V15
- V16
- V17
- V25
- V21
- V18

Note: Positions of valves is dependent on the procedure completed prior to this procedure, so valves may already be in the correct position. If not move valves to be in correct position.

Manipulating Water Flow

Observe water flow from HX-2 loop only

Note: *Cumulative time elapsed includes the time needed for startup procedure to occur.*

Step	Description	Estimated time elapsed (minutes)	Cumulative time elapsed (minutes)	Reason
1	Open CV5.	1	324	Allows flow to enter loop with pump 2 and flow to heat exchangers.
2	Turn off pump 1.	2	326	Stops any suction of cavitation in closed pipe.
3	Close CV4.	1	327	Stops water flow through loop with turbocharger.

4	Close CV2.	1	330	Allows us to test see values with the use of only one heat exchanger.
5	Run for 15 minutes.	15	345	Gives time for data collection.
6	Open CV2.	1	346	Opens flow to HX2-2.
7	Run for 15 minutes.	15	361	Gives time for data collection.

Running Washing Machine

Note: *Cumulative time elapsed includes the time needed for startup procedure to occur.*

Step	Description	Estimated time elapsed (minutes)	Cumulative time elapsed (minutes)	Reason
8	Open V23	3	364	Water flows to water heater.
9	Close V22.	2	366	
10	Run washing machine cycle once water heater is full.	60	426	
11	At beginning of wash cycle open CV3.	2	428	Allows water to drain from washing machine back into system.
12	Once cycle has finished close V23.	2	430	
13	Open V22.	2	432	Water starts bypassing washing machine again.

Redirecting Water throught HX-1 Loop

Step	Description	Estimated time elapsed (minutes)	Cumulative time elapsed (minutes)	Reason
14	Open CV4.	2	434	Allows water to flow through HX-1 again.
15	Turn on Pump 1.	3	437	
16	Open CV6.	2	439	Allows water to flow through turbo.

APPENDIX F

Pyrolysis Experimental Procedure

Introduction

This procedure outlines the instructions for setup and testing of the small scale pyrolysis of corn stover. The samples will be tested at several different temperatures, and in an inert environment of nitrogen. Testing of the different temperatures will be cross referenced with the temperature outputs of the ECL in order to determine what form of pyrolysis would be best suited for future testing with the testbed.

Materials

- Heating mantle
- Three necked flask
- Thermometer with K-thermocouple
- Distillation column with water jacket
- Three way adapter
- Collection flask
- 21 sealable test tubes for holding samples
- Elbow connector
- 3 Stands
- 3 clamps
- Gas inlet adapter with stop cock
- Solid addition flask

Experimental setup

Assemble distillation glassware and connect to water and nitrogen supply.

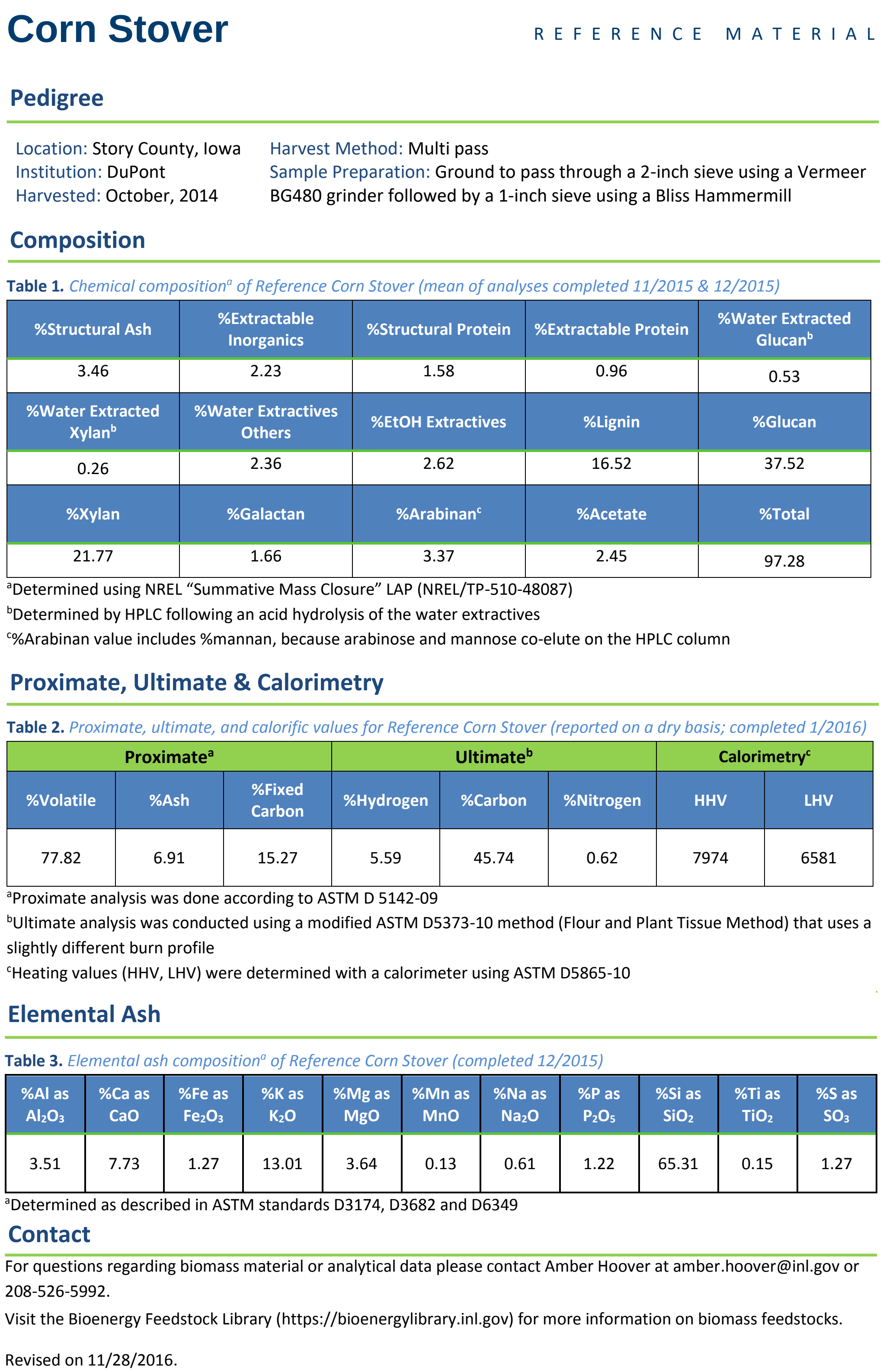
Preforming the experiment

1. Weigh empty, three necked flask and record weight.
2. Measure out 0.50 grams of ground biomass. Place in solids addition flask and attach to the distillation setup.
3. After distillation setup is complete and the biomass is in the solids addition flask, introduce nitrogen into the system, slowly.

4. Only allow nitrogen to flow for 5 to 10 seconds as to not over pressurize the system, then turn off nitrogen source.
5. Close off tube connecting nitrogen to system with a clamp to ensure no back flow occurs.
6. Turn on the heating mantle.
7. Bring the distillation apparatus up to the desired temperature while monitoring thermometer closely.
8. Introduce solids into the three necked flask.
9. Wait 10 minutes for the biomass to react.
10. After 10 minutes flush the system with nitrogen and bring back up to temperature
11. Introduce another 0.50 grams into the flask.
12. Repeat previous steps twice more.
13. Remove collection flask and transfer the content to a graduated cylinder to measure volume oil created.
14. Weigh flask and compare to the original weight.
15. Rinse the three necked flask with acetone or alcohol and dry.
16. Once dried, weigh solids left in the flask and record.
17. Clean the three necked flask and collection flask.

APPENDIX G

INL Biomass Characterization



Corn Stover

REFERENCE MATERIAL

Pedigree

Location: Story County, Iowa
Institution: DuPont
Harvested: October, 2014

Harvest Method: Multi pass
Sample Preparation: Ground to pass through a 2-inch sieve using a Vermeer BG480 grinder followed by a 1-inch sieve using a Bliss Hammermill

Composition

Table 1. *Chemical composition[a] of Reference Corn Stover (mean of analyses completed 11/2015 & 12/2015)*

%Structural Ash	%Extractable Inorganics	%Structural Protein	%Extractable Protein	%Water Extracted Glucan[b]
3.46	2.23	1.58	0.96	0.53
%Water Extracted Xylan[b]	**%Water Extractives Others**	**%EtOH Extractives**	**%Lignin**	**%Glucan**
0.26	2.36	2.62	16.52	37.52
%Xylan	**%Galactan**	**%Arabinan[c]**	**%Acetate**	**%Total**
21.77	1.66	3.37	2.45	97.28

[a]Determined using NREL "Summative Mass Closure" LAP (NREL/TP-510-48087)

[b]Determined by HPLC following an acid hydrolysis of the water extractives

[c]%Arabinan value includes %mannan, because arabinose and mannose co-elute on the HPLC column

Proximate, Ultimate & Calorimetry

Table 2. *Proximate, ultimate, and calorific values for Reference Corn Stover (reported on a dry basis; completed 1/2016)*

Proximate[a]			Ultimate[b]			Calorimetry[c]	
%Volatile	%Ash	%Fixed Carbon	%Hydrogen	%Carbon	%Nitrogen	HHV	LHV
77.82	6.91	15.27	5.59	45.74	0.62	7974	6581

[a]Proximate analysis was done according to ASTM D 5142-09

[b]Ultimate analysis was conducted using a modified ASTM D5373-10 method (Flour and Plant Tissue Method) that uses a slightly different burn profile

[c]Heating values (HHV, LHV) were determined with a calorimeter using ASTM D5865-10

Elemental Ash

Table 3. *Elemental ash composition[a] of Reference Corn Stover (completed 12/2015)*

%Al as Al_2O_3	%Ca as CaO	%Fe as Fe_2O_3	%K as K_2O	%Mg as MgO	%Mn as MnO	%Na as Na_2O	%P as P_2O_5	%Si as SiO_2	%Ti as TiO_2	%S as SO_3
3.51	7.73	1.27	13.01	3.64	0.13	0.61	1.22	65.31	0.15	1.27

[a]Determined as described in ASTM standards D3174, D3682 and D6349

Contact

For questions regarding biomass material or analytical data please contact Amber Hoover at amber.hoover@inl.gov or 208-526-5992.

Visit the Bioenergy Feedstock Library (https://bioenergylibrary.inl.gov) for more information on biomass feedstocks.

Revised on 11/28/2016.

APPENDIX H

Test One: Beginning Flow in Water Loop

Introduction

Purpose

The procedure provides the instructions needed to test the abilities water flow cycles of loop containing only pump one in the Hybrid Energy Conversion Loop for the NEUP project.

Scope

This procedure gives the actions only for the beginning of the cycle in the loop system. It shows how to begin circulating the water through one section of the system. It does not include the instructions needed to run the washing machine, dryer, or air loops. The thermal storage unit is also not being used in this procedure.

Applicability

This procedure only applies to this specific energy conversion loop design.

Precautions and Limitations

A. Pressure safety valves can release very hot air or steam to environment if pressure exceeds the design pressure.

B. Water control valves will fail open in case of emergency.

Prerequisite Actions

Performance Documents

[1] Obtain a copy of the final piping and instrumentation diagram.

[2] Obtain a copy of the final engineering drawings for reference material.

Special Tools, Equipment, Parts, and Supplies

[1] Protective, heat resistant gloves for closing and opening manual valves.

[2] Eye protection as a precaution of pressurized system breaking and ear protection if running system is overly loud.

Field Preparations

[1] Ensure water system has water in the water storage tank and piping.

[2] Proper valves must be open in the water system:

- CV1
- CV2
- CV3
- CV4
- CV7
- V22

[3] Proper valves must be closed in the water system:

- CV5
- CV6
- Vht2

[4] Proper valves must be open in the air system:

- Vht1
- V2
- V3
- Vht5
- V5
- V11
- V12
- Vht3
- Vht4
- V13
- V25

[5] Proper valves must be closed in the air system:

- V1
- V24
- V4
- V6
- V7
- V8

- V15
- V14
- V16
- V17

Testing heat transfer of air-water heat exchangers

Note: *Cumulative time elapsed includes the time needed to fill water tank and check the valves.*

Step	Description	Estimated time elapsed (minutes)	Cumulative time elapsed (minutes)	Reason
1	Fill start up compressor to 200 psi.	15	15	prepares air to flow through the system.
2	Ensure all valves are in the correct positions	10	25	Ensures flow will be directed as desired
3	Open valve on compressor and turn pressure regulator to 5 pis.	5	30	Flow starts in system.
4	Turn on air heater. Monitor T3 carefully. (do not exceed 75 C)	5	35	Heats air.
5	Turn on pump 1.	5	40	water starts flowing through HX1
7	Check flow rate at Fw1 is not exceeding 7.71 kg/hr.	3	43	Flow rate entering HX1 cannot exceed 7.71 kg/hr.
8	If air heater has reached 75 C turn off.	5	48	Heater still heats the air while it continues to flow.

9	Allow system to run.	10	58	Allows inspection of system and identification of any problem areas.
10	Turn off pump 2.	2	60	Flow can be changed to other heat exchangers now.
11	Closed CV 4 and open CV 5.	1	61	
12	Turn on pump 2. Allow system to run for 5 minutes.	5	66	Collects data on heat exchangers 2-1 and 2-2.
13	Turn off pump 2.	1	67	
14	Close CV5 open CV4	1	68	
15	Turn on pump 1.	1	69	
16	Open air valve V8	2	71	
17	Close V11, V12, and V13.	5	76	
18	Allow system to run until air heater is completely cooled.			

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