DOE-FIU SCIENCE & TECHNOLOGY WORKFORCE DEVELOPMENT PROGRAM

STUDENT SUMMER INTERNSHIP TECHNICAL REPORT

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Agitated Thin- Film Evaporator

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ABSTRACT

The Agitated Thin Film Evaporator (ATFE) being developed at the Department of Energy Hanford Site is a 1/200th scaled down version of the Wiped Film Evaporator (WFE). This system will be tested by processing actual radioactive waste streams to monitor the performance and physical behavior of the process. The ATFE will be used to remove water from streams of supernatant tank waste. It is a continuous evaporation process which is fed waste through a feed tank where waste is loaded. The system takes that waste and evaporates the water from it, condenses the water and collects it, and sends the concentrated waste back to the feed tank.

The design, development, and installation of the ATFE system are being handled by Columbia Energy and Environmental Services (CEES). In order to test the ATFE with tank waste, it will be installed into Hot Cell 1-E-1. Before this can be done, CEES will perform a mock installation of the ATFE system into the hot cell. The actual installation into Hot Cell 1-E-1 will be carried out using the available transfer tray tunnel and two manipulators available at the hot cell. These are to be used to place equipment and connect transfer lines.

The ATFE project requires that many different aspects be considered, not only for the purpose of achieving the goals of the system, but also to comply with environmental regulations and Washington River Protection Solutions (WRPS) procedures. It is known that certain tank wastes contain organic compounds and it is therefore necessary to monitor the system for output of volatile and semi-volatile organic compounds. Another concern is that of waterhammer. WRPS procedures require that waterhammer be taken into account in piping systems not only on the level of analysis but also in the pressure tests performed during validation of a system. The procedures do not differentiate between lab scale and safety significant systems in the field; therefore, waterhammer had to be considered regardless of component compliance with ASME Code B31.3. The analysis was performed by analyzing the potential for waterhammer using conservative equations.

A third consideration is the changes that may be made to the system as it progresses. For example, the ATFE must fit within a hot cell and this requires that certain modifications be made to the system. Modifications have to be made so that the system can be placed within the hot cell through the available transfer tunnel. These modifications can be simple dimension changes, or they can be more complex, such as changes to the heating system. The original hot water system was replaced with a hot oil system and this required new system parameters. In order to avoid performing a complex series of calculations every time a change is made, a spreadsheet was created to perform all of the mass and energy calculations for the system.

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1. INTRODUCTION

The tasks that were performed over the course of this internship on the Agitated Thin Film Evaporator (ATFE) were varied. For this reason, the section on research descriptions will be broken down into three main sections, each representing an individual task. The first task covered is that of organic compound sampling. This covers not just the solution to performing this sampling, but also the series of steps that were taken in order to find this method and refine the parts that were needed. The second task covered is that of the mass and energy balance calculator. This calculator simplifies the process of performing changes to the system’s parts and/or operating parameters. The final and most involved task is that of waterhammer analysis on the system. This analysis was more research oriented; it is comprised of assumptions, a process of analysis, and results. For this reason, more space within the report will be dedicated to this last task.

In order to understand this report, a basic understanding of the evaporation process is necessary. Wiped film evaporation (WFE) and agitated thin film evaporation are synonymous terms. It is a process of continuous evaporation whereby the process fluid is pumped into a heated evaporator device which contains rotating internal blades. These blades force the fluid into a thin film, hence the name, over the inner walls of the evaporator. These inner walls are actually the heat transfer area of the device. This results in rapid evaporation of the water in the process fluid because the fluid is in such a thin film that it heats up in a short amount of time.

Columbia Energy and Environmental Services (CEES) has already built and tested both a pilot and a full-scale WFE device. However, both of these devices were only tested using simulants. The objective of these devices was mainly to prove that the device works as intended and that the process is scalable. This means that the full-scale device is capable of handling anything a small-scale device can handle. The ATFE is essentially a sacrificial device which is small enough to fit within a hot cell and will be tested with actual tank waste within the hot cell. This testing will serve to validate the full-scale WFE by proving that the process works with the actual tank waste.

In the ATFE system for WRPS, there is a feed tank which contains the slurry to be processed. This slurry is a simulant modeled after AN-105 tank waste. The slurry is at an initial specific gravity (SpG) of 1.205 and the goal of the system is to concentrate the slurry to a minimum SpG of 1.5. Realistically, the SpG of the slurry will be as high as 1.693 once returned to the feed tank. A progressive cavity pump is used to draw a flow from the feed tank and this flow is sent to the evaporator device. Evaporation takes place within it and the concentrated waste is returned to the feed tank via one of the lines, referred to as the bottoms stream. The evaporate goes out of the ATFE, through a condenser, and down into a distillate tank. Once the operation is complete, a return line can be used to send the water back to the feed tank. This is done by opening the valves on the return line and pressurizing the distillate tank using a nitrogen system. This creates a flow out of the distillate tank towards the feed tank. A mixer on the feed tank can then be used to reconstitute the slurry. The process can then be repeated if desired.

2. EXECUTIVE SUMMARY

This research work has been supported by the DOE-FIU Science & Technology Workforce Initiative, an innovative program developed by the US Department of Energy's Environmental Management (DOE-EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2011, a DOE Fellow intern (Mr. Jose Matos) spent 10 weeks doing a summer internship at the DOE Hanford site in Washington State. He worked for Washington River Protection Solutions under the supervision of Ruben Mendoza and Whitney Dobson. Jose's role was to support the development of the Agitated Thin Film Evaporator (ATFE) project. Jose supported the project by finding a method for monitoring organic compounds exhausted from the system, putting together a mass and energy balance calculator, and performing a short waterhammer analysis on the lines of the system.

3. RESEARCH DESCRIPTIONS

Organic Compounds Analysis

Wastes from various tanks at Hanford have been known to contain organic compounds. The only place where these compounds could theoretically exit the ATFE and spread into the surrounding air is at the exhaust of the system's vacuum pump. Ideally, these compounds would not reach the vacuum pump at all. However, it is still important to test whether or not this takes place in the system. A method for sampling for volatile and semi-volatile organic compounds (VOCs and SVOCs) was necessary. After consulting with an organic chemist, it was found that thermal desorption unit (TDU) tubes are the scientifically accepted method of sampling for VOCs and SVOCs in air. These TDU tubes are attached to the desired air path and then placed into a gas chromatography/mass spectroscopy (GC/MS) machine.

With this knowledge, the Environmental Permitting Department at Hanford was contacted in order to procure a list of compounds of primary concern (COPC). This would dictate which types of thermal desorption tubes would be needed to monitor the exhaust of the ATFE system. After analyzing the list, it was found that tubes meeting EPA TO-17 Type 1 and Type 2 criterion would be appropriate for the analysis. The Type 1 tubes would be appropriate for monitoring of SVOCs and the Type 2 for VOCs. The material requirement for the outside of the tubes is stainless steel so that they can withstand the hot cell environment. Supelco® is the primary provider of TDU tubes to the Hanford site and they were contacted for quotes on the TD tubes. Supelco® Carbotrap™ 300 TDU tubes meet the Type 2 criteria and are available with stainless steel bodies in packages of ten. However, Supelco® does not carry off-the-shelf tubes that meet Type 1 criteria. These have to be custom built for the purpose and will be ordered when testing begins.

Another challenge presented by this task was figuring out how to attach the TDU tubes to the system. It was found that these tubes can be attached to the vacuum pump using conventional means. The vacuum pump has a standard NW/KF-25 flange on its exhaust. Using an adapter from flange to tube fitting, any ¼" Swagelok® tube fittings can be used to attach the TDU tubes to the system's exhaust. This will also allow for the tubes to be removed from the system by the available manipulators. Once removed, the tubes can be placed into conventional GC/MS machines at the 222-S labs for analysis.

Mass and Energy Balance Calculator

The ATFE is a thermodynamic process and it is necessary to control certain parameters and monitor others in order to achieve the desired system output. For this reason, CEES performed a mass and energy balance calculation and wrote a report to document it. A similar document was put together for the WFE. However, changes to the system are often necessary, particularly in the case of the ATFE. For example, the version of the ATFE described in the CEES mass and energy calculation used a hot water system in order to feed the heating jacket on the evaporator. However, it was found that this system would not fit within the hot cell and it was switched out with a hot oil system. This system operates differently and alters the results of the mass and energy balance. As opposed to having CEES perform an entirely new calculation every time such a change is made, it is useful to have a computer utility which performs the calculations. The user merely changes the input parameters and initial settings of the system and the computer can calculate the rest.

A spreadsheet was built in Microsoft Excel in order to accomplish this task. The spreadsheet breaks the system down into its 14 individual streams, providing a table for each. Each cell within these tables was given an equation which determines the value output in the cell. These equations are linked to a series of tables on the left side of the spreadsheet which contain the input parameters of the system. Certain input parameters used are actually functions of other input parameters. For this reason, the input tables also have equations within some of their cells. These input tables contain values for such parameters as initial temperature, feed rate, SpG, molal boiling point elevations at given SpG , feed volume, properties of the gases being used, etc. The output tables respond to changes in these inputs by providing new values for pressures, temperatures, viscosities, heat capacities, flow rates, energy flow, specific heats, etc. Often, the inputs are available in different unit systems (i.e. SI as opposed to American units) or certain conversions are necessary in order to obtain some of the output values. The equations in the spreadsheet have been setup such that they incorporate all of the necessary conversion factors and the user does not need to perform these conversions manually.

Although it is simple to grasp the function of the spreadsheet, obtaining a proper understanding of the mass and energy balance calculations and being able to transform them into the spreadsheet was a highly involved and time consuming process. Although the calculation lists a source for every value provided, it was often difficult to obtain the same results based on those sources. In other cases, the sources mentioned were not available or did not contain any information which would help to obtain the desired values. It was often necessary to ask questions of the contact at CEES who performed the calculation in order to verify where certain values came from and what assumptions were used to validate them. With all of this information gathered, it became possible to complete the spreadsheet.

Waterhammer

The purpose of this task was to identify which lines within the system process fluids and have the potential to hammer and to assess the magnitude and possible causes of said hammer. Each line which contained such fluids; whether water, steam, or simulant; was analyzed using conservative equations such that the obtained values would be higher than what is actually possible. Each line was also analyzed to discern if waterhammer is a possibility at all based upon the configuration of the line, the elements installed along it, and the method of operation of the line. In the case of the steam lines, it was determined that hammer would not be an issue. Also, these lines are to be replaced with oil lines, so they were removed from the analysis.

This calculation used simple spreadsheet calculations and conservative assumptions to determine the pressure rise in each line of the ATFE system. The ATFE is a rather small system, with the thickest process line having a 1” outer diameter. The maximum flow rate for the system is 10 gpm, which is only sustained for short amounts of time in line CNDS-002, and all of the valves will be opened and closed using the manipulators in the hot cell. A test performed by Highline Engineering has shown that the fastest a human hand can open or shut a valve is 0.2 seconds. The manipulators used for the ATFE testing are considerably less dexterous than a human hand and it is expected that they will take longer to open and close the valves. Taking these factors into consideration, it is highly unlikely that waterhammer will take place in the ATFE system. However, this calculation was performed in order to verify that assumption.

The formula for pressure rise used is:

$$dP = \frac{\rho a dv}{g}$$

Equation 1. Pressure Rise Formula

Where **ρ** is the weight density in lb/in^3, **a** is velocity of sound in a liquid in ft/s, **dv** is the change of velocity in (in/sec), and **g** is acceleration due to gravity in ft/s^2. This equation was taken from Becht Engineering Nuclear Services’ course: *Fitness-for-Service and Repair of Plant Piping Systems*. The value used for **ρ** is the density of water (62.4 $lb/ft^3/12^3$) lb/in^3, which is approximately 0.03611 lb/in^3, in the case of lines that run just water. For those that run simulant, the value for **ρ** is the SpG of the simulant at that point multiplied by the density of water. This value is 0.04351 lb/in^3 for most such lines with the exception of the bottoms stream which has a value of 0.061136 lb/in^3. The value used for **a** is 5096 ft/s. The value of **a** varies according to temperature. In the interest of being conservative, the **a** used was taken at the temperature which would yield the highest **a** value. Using the highest possible **a** value leads to higher values for pressure rise. Looking at the range of design temperatures listed in *CEES-Draft ATFE Line List Design Pressures Revision A*, the temperature which would yield the highest **a** value is 150°F. This **a** value is 5096 ft/s, and it was used for calculating the pressure rise in all of the lines which operate near this temperature. However, in the case of the chilled water lines which operate at 45°F and the steam lines which operate at 250°F, this value is not suitable. In both cases, this would lead to exaggerated pressure values for the lines. In the case of the chilled water, it is because of their much lower temperature. In the case of the steam, it is 100°F above 150°F and the value of **a** begins to drop after 160°F. The **a** values used for these two lines were taken at their respective temperatures. The formula calls for a **dv** value in in/sec. This presents a challenge in that the known velocity for the pipelines of the ATFE is given in gpm. In some cases, such as the 10 gpm in line CNDS-002, this flow rate was on the higher side. The flow rate was quite low in others, such as with the lines run by the feed pump which only produces 0.1 gpm at 100% of the VFD. In all cases, the maximum possible flow rates for each line were taken and converted to in^3/s. This was then divided by the cross sectional area of each tube being considered in order to convert volumetric into linear flow rate.

Finally, the value used for **g** is 32.2 ft/s^2. Using these values and formula, a pressure rise value in psi was obtained for each line in the system.

The length of a tube has an effect on the system and the time necessary to rapidly start/stop a flow. Based on this, the equation used to determine the time it takes to start or stop the flow rapidly, such that there is a risk that waterhammer will take place, is as follows:

$$t_{stop\ flow} = 2L/a$$

Equation 2. Valve Closure Formula

Where **L** is the length in ft from the pressure source to the opening or closing element and **a** is the velocity of sound in a liquid in ft/s, as before. As opposed to finding all the individual lengths from the pressure source to each individual element, a length of ten feet has been conservatively chosen for the value of **L**. This will yield a considerably slower opening/closing time for the elements involved than would be found using the shorter lengths actually found in the ATFE. The longest tube in the system is approximately 5 ft. This equation was also taken from Becht Engineering Nuclear Services' course: *Fitness-for-Service and Repair of Plant Piping Systems.*

4. RESULTS AND ANALYSIS

Figure 1 below contains screen shots from the mass and energy balance calculation. The table with the blue cell labeled “Bottoms” is one of the input tables. It accepts values from a previous input table and performs calculations for properties such as molal boiling point elevations, boiling points at given pressures, SpG, etc. The “Stream 5- Bottoms” is an output table which is linked to “Bottoms” and performs calculations for viscosity, heat capacity, flow rate range, etc based upon the values in “Bottoms.” Most input tables do not perform as many calculations, allowing the user to input values that change the outputs tables directly. The entire spreadsheet works in this manner. Figure 2 is a view of the entire spreadsheet. The tables on the left represent inputs and the ones on the right represent outputs.

Bottoms		
Molal Boiling Point Elevation @ SpG 1.10 (°F)	2.865	
Boiling Point H_2O @ 90 Torr abs (°F)	126.4	
Minimum Temperature of Bottoms (°F)	129.2	
Molal Boiling Point Elevation @ SpG 1.693 (°F)	38.02	
Boiling Point H_2O @ 110 Torr abs (°F)	133.6	
Maximum Temperature of Bottoms (°F)	171.6	
Molal Boiling Point Elevation @ SpG 1.391 (°F)	15.68	
Boiling Point H_2O @ 100 Torr abs (°F)	130.2	
Nominal Temperature of Bottoms (°F)	145.8	
Specific Gravity Range	1.1	1.693
Nominal Specific Gravity	1.391	
Sodium Molarity M_{Na} @ SpG 1.693	17.59	
Sodium Molarity M_{Na} @ SpG 1.391	9.925	

Stream 5- Bottoms

Property	Value	
Pressure Range (torr abs)	90	110
Pressure (torr abs)	100	
Temperature Range (°F)	129.2	171.6
Nominal Temperature (°F)	145.8	
Specific Gravity Range	1.1	1.693
Nominal Specific Gravity	1.391	
Viscosity Range (cPs)	1.256	4.261
Nominal Viscosity (cPs)	2.759	
Heat Capacity (BTU/lb °F)	1.007	
Flow Rate Range (gpm)	0.0288	0.0413
Nominal Flow Rate (gpm)	0.0332	
Nominal Mass Flow (lb/min)	0.385	
Nominal Water Mass Flow (lb/min)	0.189	
Nominal Nitrogen Mass Flow (lb/min)	0.0012	
Nominal Energy Flow (BTU/min)	56.5	

Figure 1. Spreadsheet screenshots.

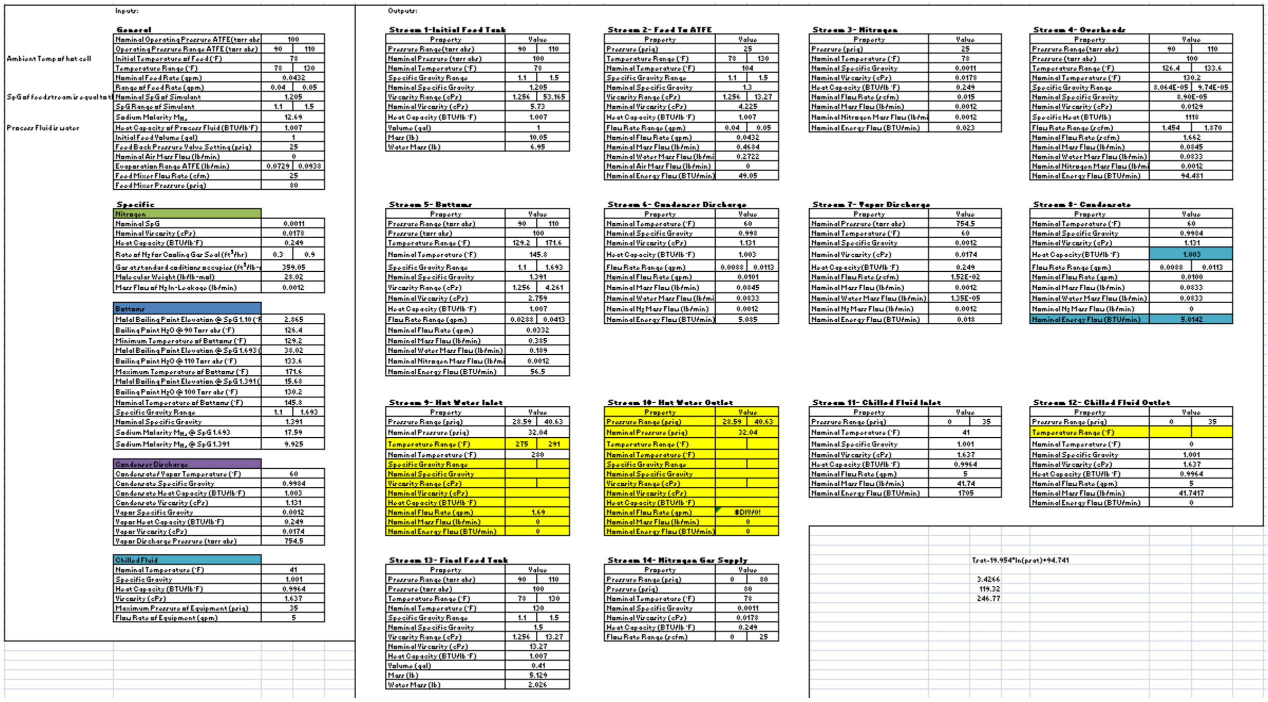

Figure 2. Overall view of spreadsheet.

Finding the components for VOC/SVOC analysis was not a research task. There are no tables to display; however, images of the components have been included for the benefit of the reader. The TD tubes on the left can be placed into a GC/MS machine like the unit on the right for performing the analysis. The unit has a carousel on top which can accept multiple tubes.

Figure 3. Tools for VOC/SVOC analysis.

The following tables contain the results of the waterhammer analysis. Table 1 presents the valve closure and opening times required to create a water hammer relative to the speed of sound in water. Table 2 presents the volumetric flow rates and other properties of the specific lines used in the calculation. Table 3 presents the pressure rise values obtained in the calculation.

Table 1. Valve Closure Times

a (ft/sec)	$T_{start/stop\ flow}$ (s)
5096	0.00392
4976.5	0.00402
4710	0.00425

Table 2. Line Properties

Line	O.D.	Flow Rate (gpm)	Flow Rate (in^3/min)	Op. Temp. (°F)	a value (ft/s)
CHW-001	0.5	5	1155	45	4,710
CHW-002	0.5	5	1155	45	4,710
CNDS-001	0.75	0.0113	2.6103	134	5096
CNDS-002	0.75	10	2310	134	5096
S-001	0.375	0.06	13.86	250	4976.5
S-002	0.375	0.06	13.86	250	4976.5
PRO-001	0.75	0.1	23.1	130	5096
PRO-002	0.5	0.1	23.1	130	5096
PRO-003	1	0.1	23.1	130	5096
PRO-004	0.5	0.1	23.1	130	5096
PRO-005	0.75	0.1	23.1	172	5096

Table 3. Pressure Rise Values

Line	O.D.	Wall Thickness (in)	I.D. (in)	Pressure Rating (psig)	dv(in/sec)	Pressure Rise (psi)
CHW-001	0.5	0.035	0.43	451	132.557	700.180
CHW-002	0.5	0.035	0.43	451	132.557	700.180
CNDS-001	0.75	0.065	0.62	3933	0.144	0.824
CNDS-002	0.75	0.065	0.62	450	127.523	728.789
S-001	0.375	0.035	0.305	550	3.162	21.263
S-002	0.375	0.035	0.305	550	3.162	21.263
PRO-001	0.75	0.065	0.62	450	1.275	8.782
PRO-002	0.5	0.035	0.43	451	2.651	18.257
PRO-003	1	0.083	0.834	300	0.705	4.853
PRO-004	0.5	0.035	0.43	4836	2.651	18.257
PRO-005	0.75	0.065	0.62	450	1.275	12.338

The following provides an analysis of the individual lines.

CHW-001/CHW-002

Rapid start or stop of pump could cause a sudden increase in pressure. However, the pump flows into the evaporator, which would allow the flow to expand, thereby dropping the pressure. The flow enters the condenser from this point and then passes out through line 002 into a tank, allowing the flow to expand once more before returning to the pump. Also, it is not possible to start/stop the pump in the 4/1000ths of a second necessary to cause a waterhammer.

CNDS-001
There are no valves on this line and no threat of waterhammer. The flow rate is a mere 0.0113 gpm. The pressure rise does not even reach 1 psi.

CNDS-002
Nitrogen is injected into the distillate tank where this line originates. The pressure from the nitrogen leads to a flow rate of 10 gpm and there are four valves along the way. Only three of these valves can actually stop the flow as one of the valves is on line ¾"-CNDS-003 which tees off ¾"-CNDS-002. This pipeline is not always in use and is only given flow during transfers between the two tanks. As a result, the valves should be open as the flow comes through and never shut during the process. The pressure spike of 728 psi is only possible if a valve were suddenly shut. Again, it is not possible to shut the valves in the 4/1000ths of a second necessary to cause a waterhammer.

S-001
There are no valves on this line. The only notable pipe element is a ¾"x 3/8" enlarger. Maximum pressure rise is a mere 21 psi.

S-002
This line comes out of the steam jacket and into a steam trap, there are no valves. The maximum possible pressure rise would also be 21 psi.

PRO-001
The feed pump pulls flow from the feed tank through this line. There is only one valve on it and the flow rate is a mere 0.1 gpm. The maximum possible pressure rise is 8.8 psi.

PRO-002
Delivers flow from the feed pump to the ATFE. There is a valve that can stop the flow right before it enters the ATFE; however, the flow rate is 0.1 gpm and the valve cannot be closed quickly enough to cause a waterhammer. The maximum pressure rise is 18.3 psi in this line.

PRO-003
PRO-003 is a short line between PRO-001 and PRO-002. It has one valve on it and its maximum possible pressure rise is just 4.8 psi.

PRO-004
PRO-004 is a short line that branches off PRO-002. It has one valve on the end which leads to a drain. The maximum possible pressure rise is 18.3 psi.

PRO-005
PRO-005 is the bottoms stream which returns concentrated waste from the WFE to the feed tank. It has two valves on it, one as it comes out of the ATFE and the other before it enters the feed tank. The maximum possible pressure rise is 8.8 psi.

5. CONCLUSION

As can be seen from the discussion, waterhammer is not a major concern for the ATFE system. The maximum possible pressure spikes due to waterhammer are 700.180 psi in the chiller lines and 728.8 psi in CNDS-002. However, neither of these pipelines can produce the conditions necessary to cause these pressure spikes. In the case of the chiller lines, there are no valves to suddenly impede the flow and there are three possible places where the flow can expand. This means that the maximum pressure could not actually be reached even if there were valves on the line which could close fast enough to cause waterhammer. In the case of CNDS-002, it is only in use when fluid is transferred back to the feed tank for reconstitution. The valves on this line will be open as this process takes place and even if proper engineering controls were not in place to control valve timing, the valves could never be closed quickly enough to cause this spike. These pressure ratings will be confirmed with burst testing before the ATFE testing actually takes place.

Overall, the longest possible amount of time necessary to open/close a valve while causing waterhammer is 4/1000ths of a second; using conservative values. A human hand can perform this at 0.2 seconds at most, with a manipulator being considerably slower. This is two orders of magnitude slower than the value needed for waterhammer to take place. Knowing these results, it is possible to move ahead with testing of the ATFE device without performing extensive waterhammer analysis on the system.

Other tasks related to the system have also been completed. The method for performing organic compounds analysis has been addressed and the necessary equipment has been located and can be procured without large delays. If any changes to the system’s operating parameters are made, there is a spreadsheet file which will provide all of the calculation results of making those changes. Overall, enough work has been done on the ATFE system to where it can be safely tested with tank waste and provide the results desired by the WTP Support Organization.

6. REFERENCES

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CEES-Draft ATFE Line List Design Pressures Revision A.

Lindeburg, Michael R. *Mechanical Engineering Reference Manual for the PE Exam*. Belmont, CA: Professional Publications, 2006. Print.

Process Piping: ASME Code for Pressure Piping, B31. New York: American Society of Mechanical Engineers, 2002. Print.

Appendix A: Line Properties

Table 4. Properties Applied to Lines

Line	ρ(lb/in3)	a (ft/sec)	$T_{start/stop\ flow}$ (s)
CHW-001	0.03611	4710	0.00425
CHW-002	0.03611	4710	0.00425
CNDS-001	0.03611	5096	0.00392
CNDS-002	0.03611	5096	0.00392
S-001	0.03611	4976.5	0.00402
S-002	0.03611	4976.5	0.00402
PRO-001	0.04351	5096	0.00392
PRO-002	0.04351	5096	0.00392
PRO-003	0.04351	5096	0.00392
PRO-004	0.04351	5096	0.00392
PRO-005	0.06114	5096	0.00392

Appendix B: Procured Lines

Table 5. Procurement Table

Line Size (inch)	Service Code	Sequence Number	Design Pressure and Temperature	Material(s)	Drawing Number	Insulation (Y/N)
1/2	CHW	001	451 psig 300 °F	316 SS ETFE	H-2-835738, Sheet 2	N
1/2	CHW	002	451 psig 300 °F	316 SS ETFE	H-2-835738, Sheet 2	N
3/4	CNDS	001	3,933 psig at 400 °F	304/304L SS	H-2-835738, Sheet 2	N
3/4	CNDS	002	450 psig 300 °F	304/304L SS 316 SS ETFE	H-2-835738, Sheet 2	N
3/4	CNDS	003	3,933 psig at 400 °F	304/304L SS	H-2-835738, Sheet 2	N
¾	PRO	001	450 psig 300 °F	304/304L SS 316 SS ETFE	H-2-835738, Sheet 2	N
1/2	PRO	002	451 psig 300 °F	304/304L SS 316 SS ETFE	H-2-835738, Sheet 2	N
1	PRO	003	300 psig 300 °F	316 SS ETFE	H-2-835738, Sheet 2	N
1/2	PRO	004	4,836 psig at 400 °F	304/304L SS	H-2-835738, Sheet 2	N
3/4	PRO	005	450 psig 300 °F	304/304L SS 316 SS ETFE	H-2-835738, Sheet 2	N

Appendix C: Speed of Sound in Water

Table 6. Values of a in ft/s

Temp (°F)	a (ft/s)
32	4,603
40	4,672
50	4,748
60	4,814
70	4,871
80	4,919
90	4,960
100	4,995
120	5,049
140	5,091
160	5,101
180	5,095
200	5,089
212	5,062

150	5096

250	4976.5

45	4710

The speed of sound can be obtained by the equation below:

$$a = \sqrt{\frac{1}{\beta \rho}}$$

Equation 3. Formula for a

Where **a** is the speed of sound, **β** is the compressibility, and **ρ** (rho) is the density. Water is almost incompressible and there were no reliable estimates of the compressibility of tank wastes available at the time of this writing. For this reason, the **a** values used are all for sound in water. This equation was obtained from *Mechanical Engineering Reference Manual for the PE Exam*.

Appendix D: P&ID

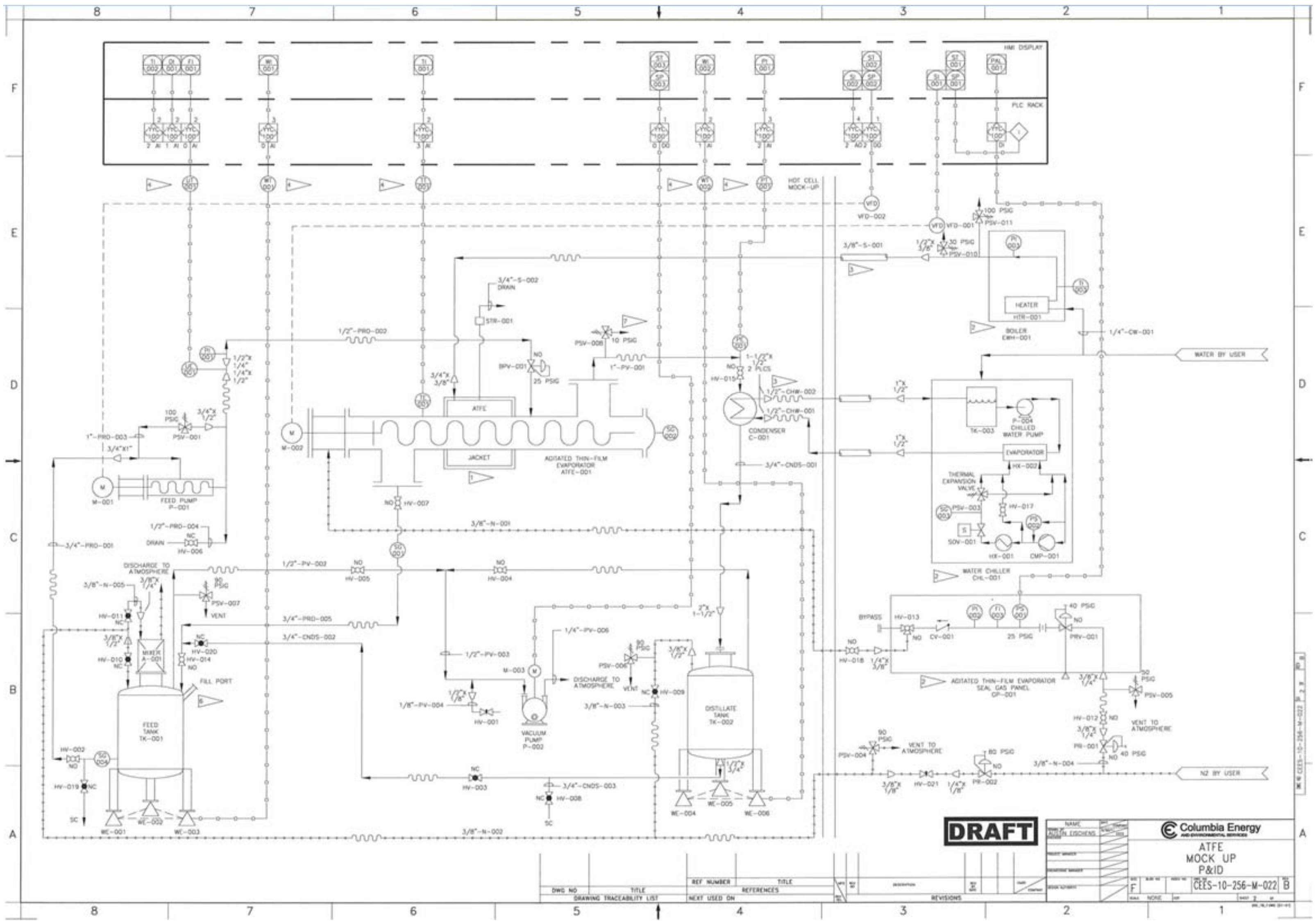

Figure 4. P&ID.

Appendix E: Formula for Speed of Sound in a Medium

19. SPEED OF SOUND

The *speed of sound* (*acoustical velocity* or *sonic velocity*), a, in a fluid is a function of its bulk modulus (or, equivalently, of its compressibility).[33] Equation 14.37 gives the speed of sound through a liquid.

$$a = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{1}{\beta\rho}} \quad \text{[SI]} \qquad 14.37(a)$$

$$a = \sqrt{\frac{Eg_c}{\rho}} = \sqrt{\frac{g_c}{\beta\rho}} \quad \text{[U.S.]} \qquad 14.37(b)$$

Equation 14.38 gives the speed of sound in an ideal gas. The temperature, T, must be in degrees absolute (i.e., °R or K). For air, the ratio of specific heats is $k = 1.40$, the molecular weight is 29.0, and the universal gas constant is $R^* = 1545.3$ ft-lbf/lbmol-°R (8314 J/kmol·K).

$$a = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{kp}{\rho}}$$

$$= \sqrt{kRT} = \sqrt{\frac{kR^*T}{\text{MW}}} \quad \text{[SI]} \qquad 14.38(a)$$

$$a = \sqrt{\frac{Eg_c}{\rho}} = \sqrt{\frac{kg_cp}{\rho}}$$

Table 14.11 Approximate Speeds of Sound (at one atmospheric pressure)

material	speed of sound m/s	speed of sound ft/sec
air	330 at 0°C	1130 at 70°F
aluminum	4990	16,400
carbon dioxide	260 at 0°C	870 at 70°F
hydrogen	1260 at 0°C	3310 at 70°F
steel	5150	16,900
water	1490 at 20°C	4880 at 70°F

Example 14.9

What is the speed of sound in 150°F (66°C) water? The density is 61.2 lbm/ft^3 (980 kg/m^3), and the bulk modulus is 328,000 psi (2.26 × 10^6 kPa).

SI Solution

$$a = \sqrt{\frac{(2.26\times10^6\ \text{kPa})\left(1000\ \frac{\text{Pa}}{\text{kPa}}\right)}{980\ \frac{\text{kg}}{\text{m}^3}}} = 1519\ \text{m/s}$$

Customary U.S. Solution

Figure 5. Reference for speed of sound.