THESIS

DESIGN OF AND EXPERIMENTATION WITH A PASSIVE VALVE-LESS FLOW-THROUGH SOLAR WATER PASTEURIZATION SYSTEM

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DAVID A. HODGSON ENTITLED DESIGN OF AND EXPERIMENTATION WITH A PASSIVE VALVE–LESS FLOW–THROUGH SOLAR WATER PASTEURIZATION SYSTEM BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE.

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ABSTRACT OF THESIS

DESIGN OF AND EXPERIMENTATION WITH A PASSIVE VALVE-LESS FLOW-THROUGH SOLAR WATER PASTEURIZATION SYSTEM

A passive solar water pasteurization system has been designed, built, and tested. The system is designed to heat water to 80°C for a minimum of one minute. A review of the available thermal inactivation data shows that this process should provide significant protection against the most common waterborne pathogens. The system is valve-less and regulates flow based on the density difference between the treated and untreated water. The system uses evacuated tube heat-pipe solar collectors with a total absorber surface area of 0.45m². A high effectiveness heat exchanger is used to recover heat from treated water and pre-heat untreated water. The system was tested in Fort Collins, Colorado, during the late summer and early fall of 2004. The daily production of treated water for the system was roughly 7.8 kg for every MJ of total daily incident radiation above 5.4 MJ. The peak production of 152 kg occurred on August 11, 2004, with a total daily incident radiation of 13.1 MJ.

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I would like to thank my advisor, Professor William S. Duff for his advice, assistance, and patience.

I would like to thank my family for their unquestioning support and patience during this long process.
DEDICATION

For my mom
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Chapter 1

Water Quality

There is a need for cost effective water treatment methods in many underdeveloped regions of the world. This thesis presents the design and experimental results of a passive valve-less solar water pasteurization system. The system is intended to be an appropriate water treatment process for rural areas, where small scale water treatment is needed.

The effectiveness of pasteurization depends on the temperature and holding time of the process. The system presented in this thesis was designed to have a typical holing temperature of 80°C and a holding time of at least one minute. These operating conditions were chosen after a preliminary review of the available thermal inactivation data of common waterborne pathogens.

The organization of the thesis is as follows. The rest of this chapter motivates the study of solar water pasteurization, by providing statistics that show there is a need for cost effective water treatment in underdeveloped regions of the world, particularly rural areas. Chapter 2 describes the waterborne pathogens that the World Health Organization (WHO) has identified to have high health significance. Chapter 3, reviews typical water treatment processes that are appropriate for small systems. Chapter 4 introduces pasteurization as a water treatment process and presents the most common way to model the thermal inactivation of microorganisms. Chapter 5 reviews the available data on the thermal inactivation of the most common water-
borne pathogens at temperatures above 70°C or holding times less than one minute. Chapter 6 reviews the work other researchers have done in the field of solar water pasteurization. Chapter 7 presents the preliminary solar water pasteurization research completed at Colorado State University. The design of the current passive valve-less solar water pasteurization system is presented in Chapter 8. Chapter 9 presents and analyzes the experimental results from the current system. Chapter 10 concludes the thesis.

1.1 The Need

The need for cost effective water treatment systems is well established. There are approximately 4 billion cases of diarrhea each year [100], resulting in 2 to 4 million deaths [101][4]. The primary cause of diarrhea is infectious disease. Many of these diseases are caused by waterborne pathogens that are transmitted via the oral-fecal cycle. Eighty percent of all illness in the developing world is caused by waterborne pathogens [1].

In 2000 The World Health Organization and UNICEF Joint Monitoring Programme for Water Supply and Sanitation released the Global Water Supply and Sanitation Assessment 2000 Report [90]. This report identified that 1/6 of the world's population does not have access to an improved water supply. This means that 1.1 billion people use water from an unprotected spring or well or rely on vendor-supplied water.

Over 4/5 of the those that do not have access to an improved water supply live in rural areas. The greatest need for potable water is in the rural areas of Africa, Asia, and Latin America. Less than half of the people that live in rural Africa have access to an improved water supply. In Latin America only 62% have access and in Asia 75% have access [90]. The goal of the Water Supply and Sanitation Council is to halve the number of people without access to improved water and sanitation services.
by 2015 [95]. To do this an average of 280,000 people must gain access to water every
day. Though this seems like a staggering task, progress has been made in the last
decade. The percentage of people with access to improved water supply increased
from 79% to 82%. This amounts to an average of 220,000 people gaining access every
day. This was done at a cost of $16 billion per year [90].

1.2 Effects of Improved Water Quality

Having access to clean water does not mean an end to diarrheal diseases. To effectively
reduce the occurrence of diarrheal diseases three things must be accomplished: 1) Improvement in water quality, 2) Improvement in sanitation: proper disposal and
treatment of fecal waste, and 3) Improved hygiene: washing hands and food and
keeping food preparation areas clean. [17]

Though improved water quality does not eliminate disease it can reduce its occur-
rence. Esrey et al. collected all available data from peer reviewed journals and found
that improved water supply quality can reduce the incidence of diarrhea by 17% [33; 34].

Since the time of Esrey’s reports several authors have studied the health effects of
having access to clean water. The results of three studies, each with a different water
treatment method, are presented here.

Iijima, et al. conducted a four-month study in Kenya in which 1,779 people drank
water that had been thermally pasteurized while 1,641 people drank untreated water.
The incidence of diarrhea for those drinking the treated water was reduced to 55% of
the incidence of those drinking untreated water. [43]

In 12-week study, also conducted in Kenya, water was disinfected with solar ra-
diation. 108 Children drank treated water and 98 drank untreated water. Severe
diarrhea was 15% less common in children that drank treated water. [25]

In Bolivia 127 households took part in a five-month study in which chemical point
of use water treatment and safe storage techniques were used to reduce the incidence of diarrhea by 44%. [70]

These examples indicate that drinking treated water improves health. A complete review of this topic is beyond the scope of this paper. No attempt was made to find all papers that report health benefits from improvements in drinking water.

In addition to health benefits there are economic benefits that occur as a result of having access to a good water supply. The time spent being sick or caring for sick children impacts productivity. The productivity improvements from water treatment may develop slowly, but they should not be ignored when analyzing the effects of a treated water supply. [49]

1.3 Conclusion

In this chapter statistics were presented that show there is a need to improve the quality of drinking water in underdeveloped rural areas. Specifically, microorganism caused diseases were discussed. The benefits of having higher quality drinking water were presented.

Though chemical contaminants (whether pollutants or naturally occurring chemicals) also pose a health risk, microorganisms are a much more common source of contamination. According the the World Health Organization “Infectious diseases caused by pathogenic bacteria, viruses, and protozoa or by parasites are the most common and widespread health risk associated with drinking-water.” [98]
Chapter 2

Waterborne Pathogens

Infectious diseases are commonly transmitted via the fecal-oral route. Infected humans or animals excrete viable pathogens. If there is fecal contamination of the water supply, infection can result from drinking water or using it to bathe or wash. The cost and relative complexity of diagnostic and detection methods make it hard to know which microorganism is responsible for a particular episode, but some microorganisms are more likely to be the cause of disease than others. The World Health Organization has identified several orally transmitted waterborne pathogens that have high health significance. [98] These pathogens include bacteria, viruses, protozoa, and one helminth. A basic description of all types microorganism can be found in many of the introductory microbiology textbooks. Introduction to Microbiology, by John L. Ingraham and Kathy Catherine A. Ingraham [44] was used as a reference for this chapter. In some cases more detailed information was obtained, in which case it is noted accordingly.

2.1 Bacteria

Bacteria are organisms that usually consist of a single prokaryotic cell. They can have many different shapes; rods, cocci, helical, etc. They are typically small compared to eukaryotic cells. The WHO identified six bacteria that have high health significance.
2.1.1 Campylobacter

*Campylobacter jejuni* and *Campylobacter coli* are gram-negative, spiral shaped, motile bacteria. The two are closely related and share clinical and epidemiological characteristics [62]. *Campylobacter* infection causes watery or sticky diarrhea that may contain blood. Fever, abdominal pain, nausea, headache and muscle pain are also common [21]. The infection lasts from 7-10 days. *Campylobacter* infects several animals. Water contamination is commonly caused by animal feces.

2.1.2 Escherichia coli

*E. coli* are Gram-negative, rod-shaped bacteria belonging the family Enterobacteriaceae. There are four recognized classes of virulent *E. coli* that cause infection in humans. The four classes are the enteroinvasive (EIEC) strains, the enteropathogenic (EPEC) strains, the enterotoxigenic (ETEC) strains, and the enterohemorrhagic (EHEC) strain designated *E. coli* O157:H7.

*E. coli* infection results in mild to severe diarrhea which can lead to dehydration. Infection of O157:H7 can cause hemolytic uremic syndrome, resulting in severe anemia and kidney failure. Healthy cattle are a significant reservoir.

2.1.3 Salmonella

*Salmonella* is a rod-shaped, motile Gram-negative bacterium. There is widespread occurrence in animals, especially in poultry and swine. *S. typhi*, the most virulent of the *Salmonella* species, causes Typhoid fever. Symptoms include weakness, confusion, headache, and most notably a very high fever. Other *Salmonella* species generally produce milder symptoms: nausea, vomiting, abdominal cramps, mild fever, and headache. Some strains of salmonella have developed antibiotic resistance.
2.1.4  **Shigella**

*Shigella* is a rod-shaped, non motile, Gram-negative bacteria. The major symptom is watery or blood streaked diarrhea. Shigella can only grow in the intestines of humans but can survive for a long time in water. Only a small number of organisms (200) are needed to cause infection.

2.1.5  **Vibro cholera**

*Vibro cholera* is a Gram-negative rod. Infection causes large secretions of chloride into the intestine. This in turn causes water and electrolytes to leave the body via osmosis. Diarrhea can be very severe and cause death in less than a day. Humans are the main reservoir but *Vibro cholera* can multiply in water.

2.1.6  **Yersinia enterocolitica**

*Yersinia enterocolitica* is a Gram-negative rod shaped bacterium. Infection causes intense abdominal pain and possible fever. Systemic infection is also possible. No animals are known to be significant reservoirs.

2.2  **Viruses**

Viruses consist of a piece of RNA or DNA, an outer coat and sometimes a membrane. Viruses can only reproduce inside a host cell. The WHO identified seven virus or virus families that have a high health significance.

2.2.1  **Adenoviruses**

Adenoviruses contain a double-stranded DNA surrounded by a protein capsid. Infection usually causes mild symptoms. Nausea, vomiting, diarrhea, abdominal pain, headache, and fever are common[21].
2.2.2 Enteroviruses

Viruses in the enterovirus family contain a naked strand of RNA. Enteroviruses include Coxsackie virus, Echovirus, and Poliovirus. Symptoms vary greatly from virus to virus, but include fever, meningitis, stomach cramps, and diarrhea.

2.2.3 Hepatitis A

Hepatitis A is a nonenveloped virus that consists of single-stranded RNA. Hepatitis A enters the body in the digestion tract and then attacks the liver. The human body produces antibodies for Hepatitis A that can be detected to provide diagnosis. Symptoms include nausea, vomiting, fatigue, and jaundice.

2.2.4 Hepatitis E

Hepatitis E is similar to Hepatitis A in that it is an RNA virus and attacks the liver. Unlike Hepatitis A no antibodies are produced by the host. In addition Hepatitis E is very dangerous to pregnant women, resulting in mortality in 15-25% of infections[57].

2.2.5 non-A, non-B Hepatitis viruses

Enterically transmitted viral infections that produce Hepatitis symptoms, but do not result in antibody production are referred to as enterically transmitted non-A, non-B Hepatitis. Hepatitis E is a named form of non-A, non-B Hepatitis.

2.2.6 Norovirus

Norovirus is a member of a family of small round structured viruses (SRSVs). They consist of a single strand RNA genome and a single structural protein. The family consists of several viruses that have been named after the places where the outbreaks occurred. The common symptoms of infection are nausea, vomiting, diarrhea, and abdominal pain[21]. Norovirus cannot be cultured in the laboratory making it difficult to study[50].
2.2.7 Rotavirus

Rotavirus consists of a double stranded RNA. The onset of infection is quick and results in watery diarrhea lasting four to seven days that can be severe and lead to dehydration. Mild and symptom free infections are possible. Rotavirus infects many mammals and birds[30]. Rotavirus is believed to cause 800,000 deaths a year and infect 95% of all children by age five[67].

2.3 Protozoa

Protozoa consist of a single eukaryotic cell, many are motile and many have complex organelles. When under stress protozoa form cysts. Cysts are resistant to UV light and chemical treatment. The WHO identified three protozoa that have high health significance.

2.3.1 Cryptosporidium

Cryptosporidium is a protozoa that infects many animals. Oocysts are present in the feces of infected animals. Intestinal infection is characterized by severe watery diarrhea. Ingestion of one organism can cause an infection. Cryptosporidium is notoriously resistant to chlorine and other chemical disinfectants.[80] Filtration has also been unreliable in the removal of Cryptosporidium from water supplies [53].

2.3.2 Giardia

Giardia is most commonly associated with beavers though it has several hosts. Giardia is common in surface water throughout the world. Many of those infected do not show symptoms. For those that do show symptoms the most common are diarrhea, abdominal cramps and weight loss. Symptoms usually last six weeks.
2.3.3 *Entamoeba histolytica*

*Entamoeba histolytica* infects humans and other primates. Most infections cause little or no symptoms. Severe infection is characterized by bloody stools and fever. Severe infection is systemic and can cause liver abscess. Cysts are transmitted via feces to new hosts.

2.4 Helminths

Helminths are multi-celled organisms commonly called worms. Only one helminth, *Dracunculus medinensis* (Guinea worm) is classified by the WHO as having high health significance in drinking water. Infection occurs when water fleas containing juvenile *D. medinensis* are ingested. The worms that can reach 60 cm make their home in connective tissues in the joints of host animals. When ready to release larvae the worm will move toward the foot or leg and penetrate the skin. The larvae are released into water and can survive for up to three weeks before being ingested by a water flea to complete their life cycle.

2.5 Conclusion

In this chapter many common waterborne pathogens were described. Treatment methods that eliminate these pathogens should result in a lower incidence of illness. For more complete information on waterborne pathogens the reader is referred to the United States Food and Drug Administration. The FDA has an online resource called the Bad Bug Book, which includes descriptions of many pathogens and gives information on recent outbreaks[21].
Chapter 3

Water Treatment Methods

Any water treatment system consists of one or more water treatment processes. Some processes are effective against a particular contaminant while another process may be more effective against different contaminants. By combining processes the effectiveness of the system is increased beyond the level that a single process could accomplish. This chapter describes a few of the many water treatment processes. The processes discussed in this chapter are those that are appropriate for small scale systems. For a more complete description of water treatment processes the reader is referred to [9] and [31]. The process descriptions in this chapter come from those two sources as well as [17; 19; 77].

3.1 Process Effectiveness and Evaluation

Before the discussion of particular processes it is important to understand the goal of a water treatment system. The composition and level of contamination varies and the system design must be sensitive to the needs of the particular situation. Each process is generally rated on its effectiveness to remove a particular pathogen. The effectiveness is commonly measured in ‘log’ terms. For example a process that produces a 5-log reduction in Campylobacter would reduce the amount of Campylobacter present in the water by a factor of 100,000.
3.2 Screening/Sedimentation

Screening and sedimentation are often called pretreatment processes. Screening removes larger objects from the water. A common application of screening is storm grates. Sedimentation is the separation of suspended particles through the use of gravity. Particles are allowed to settle to the bottom of the flow. These processes typically do not reduce the microorganism content of the water, but they prepare the water for further processing.

3.3 Roughing Filters

Roughing filters are often used to further reduce the amount of suspended particles in the water. Filtration is not screening since the size of the particles removed are smaller than the pore size of the filter. Roughing filters are commonly made with gravel. Water is forced through several gravel layers. The size of the gravel in subsequent layers is decreased. In addition to gravel, charcoal and sand can be used to increase the effectiveness of the process. Roughing filters can produce a 1-log reduction in bacteria and protozoa[17]. Wegelin et al. give a detailed description of roughing filters and present experimental results from several roughing filter designs [96].

3.4 Slow Sand Filtration

In slow sand filtration, water is filtered through about one meter of fine sand. A biological film grows on the top of the sand. This film helps slow sand filtration produce a 2-log reduction in bacteria, viruses, and protozoa [17]. The filtration rate is much slower than that of roughing filters. Visscher gives a complete description of slow sand filtration including performance expectations and required maintenance[94].
3.5 Chemical Treatments

There are many types of chemical treatment processes available. The most common is chlorine treatment. Chlorine can be added to water in either a gaseous or solid form. The effect of chlorination varies from microorganism to microorganism. Though effective, chlorine treatment requires a constant supply of chemicals. In addition, over-chlorination can be hazardous to those that consume the water. Ozone is another chemical treatment that is commonly used. To use ozone it must be produced on sight. This limits the use of ozone in rural undeveloped settings.

3.6 UV Radiation

Ultra violet (UV) radiation is a promising form of water treatment in underdeveloped rural areas. UV radiation of wavelength 200nm to 280nm can be used to breakdown DNA and RNA, making it impossible for a microorganism to multiply. The amount of radiation needed varies from microorganism to microorganism. Nieuwstad et al. conducted experiments with various bacteria and viruses and found that 420 J/m$^2$ and 960 J/m$^2$ were required to produce a 1-log reduction in the concentration of $E. coli$ and Reoviruses, respectively[63]. Water turbidity can affect the performance of a UV treatment process. Highly turbid water, from high microorganism density or other suspended particles can render UV treatment ineffective. One drawback to UV treatment is the ability of bacteria to repair their DNA. Initially all bacteria may be inactivated, but over time their viability returns. For this reason it is recommended that water treated by UV radiation be consumed within 36 hours of treatment[17].

3.7 Photochemical Disinfection

In photochemical treatment a photocatalyst or photosensitizer is used. When exposed to light a reactive species is produced. The most common catalyst is TO2. When
TO2 is exposed to UV light with wavelengths less than 387nm, electrons are excited into the conduction band. The electrons and holes created react with the surrounding liquid to produce hydroxyl and peroxyl radicals. These reactive species breakdown the contaminants in the water. The use of a photocatalyst or photosensitizer allows for the destruction of microorganisms or chemical contaminants that are not normally affected by UV radiation[26; 27].

### 3.8 Distillation

Distillation is a process in which water is evaporated to rid it of contaminants and then condensed for use. Typically distillation is used in desalination applications. The large amount of energy needed for evaporation makes this process unattractive when other process can produce similar results.

### 3.9 Pasteurization

In Pasteurization water is heated and held at an elevated temperature for a sufficient amount of time to destroy pathogenic microorganisms. Pasteurization is common for milk and other food products, but water is not commonly pasteurized. A complete discussion of pasteurization is contained in chapter 4.

### 3.10 Conclusion

This chapter described several water treatment processes that are appropriate for small scale systems in underdeveloped rural areas. By combining these processes an effective water treatment system can often be created.
Chapter 4

Pasteurization

This chapter discusses the pasteurization process in detail. Section 4.1 gives a brief history of pasteurization. Section 4.2 provides methods to model thermal inactivation of bacteria. Section 4.3 describes the effect the environment can have on the thermal stability of microorganisms. Section 4.4 points out some of the important differences between milk and water pasteurization. Section 4.5 concludes the chapter with the limitations of pasteurization as a water treatment process.

4.1 Overview and History of Pasteurization

Thermal inactivation of microorganisms was first used by Louis Pasteur in the 1860’s to help prevent spoilage of wine[69]. Since that time pasteurization has become a major part of the food processing industry. Pasteurization is a process in which the temperature of a substance is raised for a designated period of time. The goal of pasteurization is not to sterilize the substance, but rather eliminate disease causing enteric pathogens. The time and temperature used in the process depend on the properties of the substance being pasteurized. Pasteurization is most commonly associated with milk and other dairy products. Milk was first pasteurized in the 1870 by N.J. Fjord in Denmark. In the 1880’s milk was pasteurized on a commercial scale in Denmark and Sweden. The large-scale pasteurization of milk began in the United States at the start of the 20th century[83]. Milk is currently pasteurized in one of
three ways: 1) Low-Temperature Holding (LTH) where a temperature of 63°C is maintained for 30 minutes. 2) High-Temperature, Short-Time (HTST) where a temperature of 71°C is maintained for 15 seconds. 3) Ultra-High-Temperature (UHT) where a temperature of 141°C is maintained for 2 seconds[22]. In addition to milk, many juices, egg products, and some meat products are pasteurized.

## 4.2 Modeling Pasteurization

Several mathematical models are used to describe the thermal destruction of microbes[11; 12; 72]. The simplest and most commonly used method is the log-linear model. The use of this model is described in section 4.2.1. Section 4.2.2 discusses the observed deviations from the log-linear model.

### 4.2.1 Log–Linear Idealization

When a medium that contains microorganisms is heated to an elevated temperature the concentration of viable microorganisms is typically observed to decrease exponentially with time. This behavior can be expected when each individual organism has the same heat resistance and when each microorganism has a constant chance of inactivation per unit time[40]. The time it takes to achieve a 1-log reduction in the microorganism at a specified temperature in a specified medium is called the decimal reduction time (D-value) for the microorganism at the given temperature in the given medium. Often the notation \( D_{T_0} \) is used to indicate the D-value at the temperature \( T_0 \). If the D-value is known the surviving fraction \( f \) of a microorganism can be found with equation 4.1.

\[
f = 10^{-t/D}
\]  

(4.1)

If the base ten logarithm of the surviving fraction is plotted as a function of time a straight line is achieved with the magnitude of the slope equal to the D-value, as shown in figure 4.1.
Since microorganisms are inactivated quicker at higher temperatures the D-value of a microorganism increases with temperature. The temperature increase (drop) needed to decrease (increase) the D-value by ten fold is called the z-value. In the idealized case the z-value is constant for a microorganism. If the D-value is known at one temperature $T_1$, the z-value can be used to determine the D-value at another temperature $T_2$.

$$\log(D_{T_2}) = \frac{T_1 - T_2}{z} + \log(D_{T_1})$$ (4.2)

Figure 4.1 shows survival curves for an ideal microorganism, ‘Ideal microorganism A’, at two temperatures. The D-value associated for each temperature can be found by determining the slope of each line (or equivalently, the time needed for a 1-log reduction in survivors). In this case $D_{T_1} = 5$ seconds and $D_{T_2} = 2.5$ seconds. If $T_2$ and $T_1$ are known then the z-value can be determined with equation 4.2. For example if $T_1 = 70^\circ$C and $T_2 = 80^\circ$C then $z = 33.2^\circ$C. It would take a change in temperature of $33.2^\circ$C to cause a tenfold change in the D-value.

If there is a reduction requirement, $f$, for a microorganism with a know D-value, equation 4.1 can be solved for the required time, $t$, resulting in equation 4.3.

$$t = -D \log(f)$$ (4.3)

For an ideal microorganism knowing the D-value at one temperature and the z-value is enough to predict the effect of any thermal inactivation process. If $D_{T_0}$ is the D-value of the microorganism at $T_0$ and $z$ is constant, equation 4.2 and equation 4.3 can be combined to find the minimum holding time required to produce the desired reduction, $f$, for a constant temperature process.

$$t = -D_0 \log(f)(10)^{-\frac{T-T_0}{z}}$$ (4.4)

For an ideal microorganism with a known reduction requirement, plotting the minimum holding temperature as a function of the base ten logarithm of the minimum holding time results in a straight line, sometimes called an inactivation curve. As an
Figure 4.1: Surviving Fraction of an Ideal Microorganism at Two Temperatures
example the inactivation curve for 5-log reduction ($f = 1 \times 10^{-5}$) in ‘Microorganism A’ is shown on figure 4.2 (dashed line). This line can also be constructed with the information on figure 4.1: The survival curve for $T_1 = 70^\circ C$ predicts a 5-log reduction after 25 seconds. At $T_2 = 80^\circ C$ a 5-log reduction occurs after 12.5 seconds. These two points (the circles on figure 4.2) define the line of the inactivation curve. Figure 4.2 also shows the inactivation curve of ‘Microorganism B’ (solid line) which has a $D_{60}$-value of 30 seconds, a z-value of 5C°, and a 6-log reduction requirement ($f = 1 \times 10^{-6}$).

Three constant temperature processes are also shown on figure 4.2. ‘Process A’ has a temperature of 75°C and a holding time of 10 seconds; ‘Process B’ has a temperature of 60°C and a holding time of 100 seconds; ‘Process C’ has a temperature of 70°C and a holding time of 40 seconds. For a process to be effective against a particular microorganism it must lie above and to the right of the inactivation curve. If the inactivation curves of all target microorganisms are known a ‘Safe Region’ can be constructed. The ‘Safe Region’ is the area above and to the right of all inactivation curves. ‘Process A’ will result in the desired inactivation of ‘Microorganism B’, but not ‘Microorganism A’. ‘Process B’ will result in the desired inactivation of ‘Microorganism A’, but not ‘Microorganism B’. ‘Process C’ will result in the desired inactivation of both ‘Microorganism A’ and ‘Microorganism B’.

For processes that do not have a constant temperature, that is $T = T(t)$, equation 4.3 can be solved for $\log(f)$ and then integrated, resulting in equation 4.5.

$$\log(f) = \int_0^t \frac{-dt}{D(10)^{\frac{T(t) - T_0}{z}}}$$  \hspace{1cm} (4.5)

The integral of equation 4.5 is typically not evaluated. It is common to approximate a temperature varying process with a series of constant temperature processes and then apply equation 4.1 iteratively [88; 40].

A more conservative method of determining the thermal lethality of a time varying process is to calculate the cumulative time the process is above a given temperature, $T$. For example, consider the two time varying processes shown if figure 4.3 : In
Figure 4.2: Inactivation Curves For ‘Microorganism A’ and ‘Microorganism B’. Only ‘Process C’ will result in the desired reduction of both microorganism.
'Process D' (dashed line in figure 4.3) water is heated at a constant rate from 20°C to 60°C in 30 seconds, held at 60°C for 90 seconds, heated from as a constant rate from 60°C to 80°C in 15 seconds, cooled back to 60°C in 15 seconds and then quickly cooled to 20°C. In 'Process E' (solid line in figure 4.3) water is heated at a constant rate from 20°C to 80°C in 30 seconds, held at 80°C for 20 seconds and then cooled back down to 20°C in 30 seconds.

The cumulative time (in seconds) 'Process D', and 'Process E' are over temperature, $T$, are given by equations 4.6 and 4.7, respectively.

$$t_D(T) = \begin{cases} \frac{3}{4} (60 - T) + 90 & : 20 < T \leq 60 \\ \frac{3}{2} (80 - T) & : T > 60 \end{cases} \quad (4.6)$$

$$t_E(T) = (80 - T) + 20 : 20 < T \leq 80 \quad (4.7)$$

Figure 4.4 shows equation 4.6 for 'Process D' and equation 4.7 for 'Process E' overlayed on the survival curves of 'Ideal Microorganism A', and 'Ideal Microorganism B'. Since parts of both process curves lie above both inactivation curves, both process will result in the desired inactivation of both microorganisms. Note that 'Process D' is not above both inactivation curves at the same time. The conservative method of constructing a safe region from inactivation curves would reject 'Process D'.

4.2.2 Deviations from Linear Behavior

Real microorganisms deviate from the linear behavior described in section 4.2.1 in a few important ways.

The thermal inactivation of microorganisms in not completely exponential with time. A typical survival curve is shown in 4.5. There are three distinct regions to this curve, the shoulder, the linear region and the tail. At the start of heating the thermal destruction may be slower than predicted by the D-value for the microorganism. It is actually possible for the number of viable organisms to go up. There are a few explications for the shoulder. First, some dormant cells may be thermally activated.
Figure 4.3: Temperature profiles for ‘Process D’ and ‘Process E’
Figure 4.4: Process curves for ‘Process D’, and ‘Process E’ show that both processes achieve the desired inactivation of ‘Microorganism A’ and ‘Microorganism B’.
Figure 4.5: Typical surviving fraction curve for a real microorganism. The shoulder and tail are departures from the log-linear model.
Second, cells clumped together or to other particles may heat up more slowly than the fluid they are suspended in. Lastly the common method for determining the number of viable bacteria is to grow the bacteria on auger plates and count the number of colonies. If two or more cells are clumped together they will only form one colony. Heating may break clumps apart and increase the number of colony forming units. To account for the shoulder region a delay value can be used. If a delay value is used, the D-value represents the inactivation rate after shouldering. For example the data on figure 4.5 could be modeled with a delay of five seconds and a D-value of approximately three seconds.

Organisms may also persist for longer than expected resulting in a tail. Tailing is possibly caused by clumping, the existence of individual microbes with higher than normal thermal tolerance, or from an increase in thermal resistance due to heat stabilizing protein production triggered by the heating process itself [40]. The use of a delay value does not correct the model for tailing.

Another way that real microorganisms deviate from ideal behavior is that the z-values of real microorganisms are only constant for a narrow temperature range. This means that results from experiments conducted in one temperature range should not be extrapolated to other temperature ranges.

Because of the inaccuracies of the log-linear model other thermal inactivation models are sometimes used [40; 88]. Since most researchers investigating the thermal inactivation of microorganisms report results in terms of the log-linear model, other models are not presented in this thesis.

4.3 Environmental conditions that affect thermal resistance

The media that a microorganism lives in can affect its thermal resistance. In liquids the amount and nature of suspended particles can change the thermal resistance of
microbes. Particles slow the heating process on a local level and provide thermal protection to microbes. In solid foods the fat content can affect thermal stability. Increasing the fat level tends to increase the thermal resistance of microbes (some exceptions have been found [47]). Increasing the salt level has also been found to greatly increase thermal resistance [61; 66]. The pH of the media can also affect the thermal resistance. As a way to minimize the effect of pH microbes can be acid–adapted. Acid–adapted microorganisms are cultured in a media that has the same pH as the media used in the thermal inactivation test.

In addition to the media that the microorganism lives in, the thermal history of the microorganism affects its thermal resistance. Many microorganisms produce thermal stabilizing proteins. Microbes that have been thermally shocked (e.g. exposed to a high temperature for a short amount of time) can have increased thermal resistance[14; 40; 76].

4.4 Milk vs. Water Pasteurization

Milk has a long history of pasteurization and it may be tempting to assume that adopting the same standards used on milk [22] would result in sufficient water treatment. There are two reasons why this simple approach cannot be used. First, the microbiological content of water and milk are different. Water has different microorganisms with different contaminant concentrations. Second, and more important, milk is treated as a perishable item. After pasteurization milk is required to be refrigerated and then consumed in a short amount of time or discarded[22]. Though raw water does not contain the nutrients milk contains and microbe growth will therefore not be nearly as rapid in water, growth is still possible in raw water. In most areas where water treatment is needed there is no way to refrigerate water after treatment. Water is not commonly thought of as perishable so any treatment method should aim to give treated water a very long shelf life. This requires that any pasteurization
process used to treat water should aim to completely destroy all enteric pathogens.

4.5 Conclusion

This chapter has described the process of pasteurization and provided methods to model thermal inactivation of microorganisms. Pasteurization is limited in two ways. First, there are many microorganisms that thrive at high temperatures. So far no pathogenic organisms have been found to be thermotolerant[17], but there is the possibility that virulent organisms will develop thermotolerant strains or that thermotolerant organisms will develop virulence factors. The second limitation is that pasteurization will not remove chemical contaminants. On a global scale microorganisms are a much more common source of contamination [98], but pasteurization is not an appropriate water treatment process in local areas where chemical contamination is significant.
Chapter 5

Review of Thermal Inactivation of Waterborne Pathogens at or Near HTST Pasteurization Conditions

This chapter reviews the thermal inactivation data for those microorganisms that the WHO has classified to have a high health significance[98]. To be consistent with the conditions of typical flow-through solar water pasteurization systems, data was collected from studies that had an operating temperature of at least 70°C or showed significant reduction in infectivity for holding times of one minute or less. Section 5.1 discusses preliminary information about thermal inactivation experiments. Section 5.2 presents the results of previous reviews of thermal inactivation data. Sections 5.3, 5.4, and 5.5 present thermal inactivation data for bacteria, viruses, and protozoa, respectively. Section 5.6 concludes the chapter with a summary of the collected data.

In sections 5.3–5.5 data is only presented for those pathogens the WHO classified to have a high health significance even if the original publication included other microorganisms. In addition only data for the most pertinent suspension media, temperature, and holding time are discussed.

Thermal inactivation data for guinea worm was not collected. Since the time that the WHO classified the helminth to have a high health significance it has been targeted for eradication. It is now confined to just 13 countries in Africa, with most of the cases in Sudan where civil war and genocide have hindered the progress of
5.1 Considerations in Reviewing Thermal Inactivation Data

This section presents some important considerations when evaluating thermal inactivation data. This section is not meant to be a review of microbiological techniques or even as an introduction to microbiological techniques. This section is only intended to give the reader sufficient background to understand the data presented in sections 5.2 through 5.5.

5.1.1 Media

As mentioned in section 4.3, the media a pathogen is suspended in during testing can affect its thermal resistance. In addition, the media used for culturing or enrichment as well as the temperature, length, and conditions of incubation may affect the calculated pathogen concentration both before and after treatment.

Since the author of this thesis has no expertise in culturing waterborne pathogens the culturing methods of individual researchers are not discussed in this chapter. The interested reader should consult the original publications for details.

5.1.2 Heating Method

The method used to heat the test samples can greatly affect the results. In general it is desirable to heat the samples to the process temperature as quickly as possible and then, after the holding time, cool them as quickly as possible. There are two classes of heating methods in thermal inactivation experiments; batch heating and flow heating.

There are three common protocols used in thermal inactivation experiments. The first method involves inoculating test tubes (or some other vessel) with a known concentration of a microorganism and then submerging the sample in a constant
temperature water bath for a specified time. The disadvantage of this method is that heating is not uniform and the thermal mass of the sample can create a significant warm up period. The second method is to first place media filled test tubes in a constant temperature water bath and then add a known concentration of the pathogen after thermal equilibrium is established. This method results in uniform heating without a significant warm up period. The disadvantage of this method is, if not performed correctly, some microorganisms may be deposited on the wall of the test tube above the suspension media. The wall of the test tube may not reach the same temperature as the rest of the sample, resulting in surviving pathogens[82; 91]. The third batch method used is to inoculate capillary tubes and then submerge them in a water bath. Capillary tubes have a large ratio of surface area to volume and therefore heat much quicker than other vessels.

In all three methods it is important that the entire sample is submerged in the water bath to ensure proper heating of all pathogens[91].

For liquids, flow heating can be accomplished with heat exchangers that rapidly heat and then cool inoculated media. Heat exchangers can have significant thermal mass so it is important that steady state temperatures are achieved before data is collected. Juneja and Miller [48] provide the design for a Submerged Coil Heating Apparatus (SCHA) in which inoculated media flows through a stainless steel coil submerged in a water bath. From the coil the liquid is automatically dispensed into test vials.

5.1.3 Enumeration Methods

To enumerate bacteria they are usually plated on media and then the number of colonies is counted. For highly concentrated bacteria serial dilutions are made until a countable number of colonies results. For low concentrations, samples can be added to enrichment broth and incubated to increase the concentration to a measurable
level. By knowing the level of dilution (or enrichment) the concentration of colony forming units (cfu) in the original sample can be calculated.

For viruses that can be cultured in the laboratory it is common to inoculate tissue and then count the number of plaques. Plaques indicate cell infection. Through dilution or enrichment the concentration of plaque forming units (pfu) in the original sample can be calculated. Some viruses, most notably Norovirus cannot be cultured in the laboratory[50]. To study these viruses either model viruses (that are expected to have similar thermal resistance) are studied or volunteers are inoculated to determine the effectiveness of a treatment process.

The most straightforward method to enumerate protozoa is through cytology in which the number of viable organisms in a small sample are directly counted. Tissue cultures can also be inoculated with samples of protozoa. Comparative analysis of infectivity can then be used to determine the pathogen concentration.

Since the author of this paper has no expertise in enumerating waterborne pathogens the enumeration methods of individual researchers are not discussed in this chapter. The interested reader should consult the original publications for details.

5.1.4 Data Extrapolation

There are two ways in which thermal inactivation data is commonly extrapolated from experiments. First, it is common to calculate z-values and then extrapolate data to higher temperatures using the log-linear model. As mentioned in section 4.2.2, z-values are only constant over a limited range and extrapolation to different temperature ranges may not be accurate. Second, it is common to measure the rate of inactivation over a short time period and then assume a constant rate to predict the inactivation level after a longer period. If the microorganism exhibits any tailing, extrapolating to long holding times will result in large errors in the
predicted inactivation. Both types of extrapolation can result in an over estimate of the effectiveness of a process. No extrapolation is reported in this chapter even if the original author(s) included extrapolation in their results.

5.2 Existing Reviews of the Thermal Resistance of Waterborne Pathogens

Several researches [17; 24; 85] that have investigated solar water pasteurization cite the work of Feachem et al.[37] to establish the potential effectiveness of the pasteurization process. Feachem et al. compiled the thermal inactivation studies for many microorganisms and studied the typical contamination concentrations. From this information Feachem et al. predicted the minimum time and temperature requirements for effective pasteurization processes and constructed a ‘Safe Region’. (The ‘Safe Region’ was constructed in the same manner as the example in section 4.2.1 as shown in figure 4.2.) Burch and Thomas [18] noted that of the data Feachem et al. collected enteric viruses were the most resistant to high temperatures and proposed equation 5.1 as a way to calculate the minimum holding time, \( t \), in hours required to effectively inactivate viruses (and therefore all other microorganisms) as a function of the Celsius holding temperature, \( T \).

\[
t = 1.47 \times 10^7 \times e^{-0.265T}
\] (5.1)

Unfortunately the data collected by Feachem et al. is for lower temperatures and significantly longer holding times than those typical of flow-through solar water pasteurization processes. Equation 5.1 requires significant extrapolation and it’s validity is not known.

In 1977 Larkin [51] completed an exhaustive review of the thermal inactivation of viruses and concluded that heating to 71° C for one minute should provide adequate protection. Since that time, Norovirus and Rotavirus have been identified as important enteric pathogens.

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5.3 Bacteria

Probably because they are the easiest microorganism to culture there is significant information about the thermal inactivation of many waterborne bacteria. Unfortunately most of the published data is for relatively low temperatures and long holding times when compared to the typical operating conditions of a flow-through solar water pasteurization system.

Bandres et al.[7] report thermal inactivation data for *E. coli* (ETEC), *Shigella sonnei*, *Salmonella* B, and *Campylobacter jejuni*. For each microorganism, 100 ml of water was initially inoculated to a concentration of $10^7$ microorganisms per ml and heated on a hot plate from 23°C to 100°C. Samples were removed after heating to 55°C, 60°C, 65°C, 75°C, and 100°C.

The heating process was so slow that it is impossible to determine D-values. Only very conservative estimates can be made. After heating for at least seven minutes and reaching a temperature of 65°C all microorganisms experienced at least a 6-log reduction in concentration. The process of heating water from 23°C to 65°C is certainly less lethal than a process with a constant temperature of 65°C, so the lower limit of the $D_{65}$-value of all four microorganisms is 71 seconds.

Bradshaw, et al.[15] report the thermal resistance of 37 outbreak related strains of *Salmonella typhimurium*. Samples of milk were initially inoculated to a concentration of $10^5$ cells/ml. The samples were dispensed into 13-mm by 100-mm borosilicate glass tubes, sealed, and then heated in a water bath at 51.8°C. In addition a representative strain, 4SCBS, was heated to four temperatures between 51.8°C and 68.3°C. A $D_{51.8}$-value of 24 minutes was reported for 13 strains isolated from patients and a $D_{51.8}$-value of 22.8 minutes was reported for 24 strains isolated from milk. A $D_{68.3}$-value of 0.9 seconds was reported for strain 4SCBS. The holding times and final concentrations of the *Salmonella* were not reported. It is also not clear if there was significant tailing during the heating process or if the D-values reported were adjusted.
D’Aoust, et al. [28] studied the thermal inactivation of 15 strains of *Campylobacter*, 15 strains *Yersinia enterocolitica*, and ten strains of *Escherichia coli* 0157:H7 in milk. For each microorganism milk was initially inoculated to a level of approximately $10^5$ cfu/ml. Samples were heated in regenerative plate pasteurizer operated from $60^\circ C$ to $72^\circ C$ with a holding time of 16.2 seconds.

Heating to $60^\circ C$ resulted in a 2-log reduction in *E. coli* and a 4-log reduction in both *Yersinia enterocolitica* and *Campylobacter*. There were no detectable survivors for any of the microorganisms when heated to at least $64.5^\circ C$. The detection limit was not reported.

Evans et al. [35] used a plate heat exchanger to study the heat resistance of ten strains of *Escherichia coli*, five strains of *Salmonella typhosa*, and five strains of *Shigella dysenteriae*.

The most resistant strain of *Escherichia coli* went from an initial concentration of $2 \times 10^6$ cfu/ml to a final concentration of less than $10^{-3}$ cfu/ml when heated to a maximum temperature of $76.7^\circ C$ for a total heating and cooling time of six seconds, resulting in a $D_{76.7}$-value of 0.25 seconds.

The most resistant strain of *Salmonella typhosa*, ATCC 9993, went from an initial concentration of $2 \times 10^6$ cfu/ml to a final concentration of less than $5 \times 10^{-3}$ cfu/ml when heated to a maximum temperature of $73.9^\circ C$ for a total heating and cooling time of six seconds, resulting in a $D_{73.9}$-value of 0.21 seconds.

The most resistant strain of *Shigella dysenteriae*, ATCC 9683, went from an initial concentration of $10^6$ cfu/ml to a final concentration of less than $5 \times 10^{-3}$ cfu/ml when heated to a maximum temperature of $71.1^\circ C$ for a total heating and cooling time of six seconds, resulting in a $D_{71.1}$-value of 0.20 seconds.

Groh et al. [41] studied the thermal resistance of *Escherichia coli*. Flasks of water were heated to $50^\circ C$, $60^\circ C$, $70^\circ C$, and $100^\circ C$. Each flask was then inoculated with...
*E. coli* to a concentration of approximately $5 \times 10^5$ cfu/ml. 0.001 ml was removed immediately after inoculation and again after 1 minute, 5 minutes and 10 minutes. For water heated to $70^\circ C$ or higher no survivors were detected. Due to the methods used the minimum detectable concentration was relatively high compared to other studies.

Line et al. [54] studied the thermal resistance of *Escherichia coli* 0157:H7 in ground beef. Beef was inoculated to a concentration of $10^7$ cells/gram. One gram samples were then heated to $62.7^\circ C$ for 15 seconds, 30 seconds, and 45 seconds. There was no noticeable shouldering or tailing and $D_{62.7}$-value of 18 seconds was calculated.

Lovett et al.[55] studied the thermal inactivation of three strains of *Yersinia enterocolitica* in milk. 1.5 ml samples with an initial concentration of $10^7$ to $2 \times 10^7$ cfu/ml were place in 13-mm x 100-mm Pyrex tubes and then heated in water baths. The heating temperature varied from $51.7^\circ C$ to $68.3^\circ C$. Samples were removed in thirty second intervals. For the most resistant strain, C 1017, a $D_{62.8}$-value and a $D_{68.3}$-value of 57.6 seconds and 5.4 seconds were calculated, respectively. The observed holding time was adjusted to account for the heating and cooling process as described in Anelliss et al.[3].

Mak et al.[56] studied the thermal inactivation of a six strain cocktail of *Escherichia coli* O157:H7 and three strain cocktail of of *Salmonella* spp. in apple cider using a plate heat exchanger. A 5-log reduction in both nonadapted and acid-adapted *E. coli* was found for a process with a 14 second holding time and a temperature of $68.1^\circ C$. 14 seconds at $71.1^\circ C$ resulted in a 6.6-log reduction of *E. coli*. For *Salmonella* a 5-log reduction was achieved in 14 seconds with a temperature of $65.6^\circ C$.

Mazzotta [58] studied the thermal resistance of acid-adapted *Escherichia coli* O157:H7 and *Salmonella enterica* in fruit juices. Flasks containing 150 ml of juice were heated in a constant temperature water bath. Once an equalibrium temperature was reached the flasks were inoculated with the microorganism to an initial concen-
tation of approximately $10^5$ cells per ml. The final concentration and holding times were not reported. The $D_{60}$-values of acid adapted *E. coli* were calculated to be 1.5 minutes, 1.7 minutes, and 1.2 minutes in apple, orange, and white grape juice, respectively. The maximum $D_{62}$-value of acid adapted *Salmonella* was calculated to be 12 seconds, 30 seconds and 22 seconds in apple, orange, and white grape juice, respectively.

Michalski et al.[61] used capillary tubes to study the thermal resistance of *Salmonella enteritidis* in egg products. Liquid hole eggs were inoculated with $10^9$ to $10^{10}$ cfu/ml. Capillary tubes were filed with 100 $\mu$m of inoculated egg and then placed in a 64°C water bath. Tubes were removed and immediately placed in an ice bath after three, six, nine and twelve seconds. A $D_{64}$-value of 2.4 seconds was calculated.

Palumbo et al. [66] studied the thermal resistance of *Salmonella* in egg products. 0.5 ml samples with initial concentrations of $8.5 \times 10^{10}$ to cfu/ml were placed in 15-mm x 60-mm glass vials and placed in a 64.4°C water bath. Timing started when the sample reached the bath temperature. Final concentrations and holding times were not reported, but there was no noticeable tailing. A $D_{64.4}$-value of 18 seconds was reported.

Shultz et al. [78] studied thermal inactivation of *Vibrio cholerae* in peptone water. 13 mm x 100 mm tubes were filled with 6-ml samples having an initial concentration of $10^6$ cells/ml. The tubes were submerged in a 63°C water bath. The tubes were removed at fixed intervals and cooled in an ice bath. Tubes were submerged up to 2.67 minutes and a 7-log reduction was calculated to take 2.59 minutes resulting in a $D_{63}$-value of 21.6 seconds.

Sörqvist [82] investigated the thermal resistance of three strains of *Yersinia enterocolitica* two stains of *Campylobacter coli*, and one strain of *Campylobacter jejuni*. Capillary tubes were inoculated with initial concentrations between $10^6$ and
10^7 cfu/ml. After inoculation, the capillary tubes were placed in a 60°C water bath. 

_Yersinia_ samples were heated for 15, 30, 60, 90, 120, and 150 seconds. _Campylobacter_ spp. samples were heated for 10, 15, 20, 25, 30, 40, and 45 seconds. After heating the capillary tubes were cooled in ice water. For the most resistant strain of _Yersinia enterocolitica_ the _D_\textsubscript{60}-value was calculated to be 33 seconds. The _D_\textsubscript{60}-value of _Campylobacter jejuni_ and _Campylobacter coli_ were calculated to be 7.8 and 10.2 seconds, respectively.

Toora et al. [92] studied the thermal resistance of _Yersinia enterocolitica_ in whole and skim milk. Two flasks, one containing 99-ml of skim milk and one containing 99-ml of whole milk were preheated in a water bath to a temperature of 62.8°C. 1-ml of a six strain cocktail was then added to both flasks. The initial concentration in the flasks was 1.5 × 10^7 cfu/ml. Small samples were then removed from the flask after 10, 20, 30, 40, 50, and 60 seconds and cooled in an ice bath. _D_\textsubscript{62.8}-values of 10.5 and 10.3 seconds were calculated for whole and skim milk respectively.

### 5.4 Viruses

There is limited information about the thermal inactivation of viruses at high temperatures. Culturing viruses (when possible) is generally more complicated than culturing bacteria. Unfortunately enteric viruses often have higher thermal resistances than enteric bacteria so bacteria cannot be used as indicator organisms. An additional complication with viruses is that it is possible to destroy a virus, but not destroy the RNA of the virus. The liberated RNA may also be infectious[52].

Bidawid et al. [10] studied the thermal resistance of Hepatitis A (HAV) in skim milk, whole milk, and cream. U-shaped capillary tubes were inoculated with 100-\textmu m of milk with an initial concentration of 2 × 10^6 pfu/ml and then placed in constant temperature water baths of various temperatures. Samples were exposed to 75°C for 0.5, 1, 2, 4, 6, 8, 10, 12, 14, and 16 minutes. Samples were exposed to 80°C for 0.5, 1,
1.5, 2, 2.5, 3, 3.5, 4, 5, and 6 minutes. Samples were exposed to 85°C for 0.5, 1, 1.5, 2, 2.5, 3, 3.5, and 4 minutes. Measurement of titer levels was done by plaque assay. The time required for a 5-log reduction in the titer of skim milk for exposure at 75°C, 80°C, and 85°C was 5.45 minutes, 36 seconds, and less than 30 seconds, respectively. Significant tailing was experienced at all temperatures. Titer reduction beyond 5-log could not be measured.

Parry and Mortimer [68] studied the thermal inactivation of Hepatitis A Virus in milk and phosphate-buffer saline. A tissue culture method was used to determine the effectiveness of the process. First cells were infected with known concentrations of HAV and the antigen production was measured. This correlation was used to determine the titer of treated samples. Heating to at least 80°C for at least 5 seconds resulted in no detectable level of residual infectivity. From the reported data it appears that the maximum detectable reduction was 3-log.

Slomka and Appleton [79] studied Feline Calicivirus as a model system for Norovirus. Norovirus, a small round structured virus cannot be cultured in the laboratory, but feline calicivirus can be cultured and has similar structure. Infected cockles were boiled and there internal temperature was monitored. After boiling for 30 seconds the average internal temperature was under 65°C and no inactivation was detected, after 1 minute the average internal temperature was 78°C and no virus could be cultured from the cockles, but RNA was still detectable via RT-PCR (reverse transcription polymerase chain reaction) until 2 minutes when the average internal temperature was approximately 95°C.

Stazynski et al.[87] studied the thermal inactivation of Poliovirus type 1 (an entero-virus) in water. The infectivity before and after treatment was determined by plaque-titration. Heating to 72°C for a holding time of 30 seconds resulted in at least a 5-log reduction in titer.

Sullivan et al. [89] studied the thermal resistance of several viruses including Ade-
novirus 12. A conservative $D_{52}$-value for adenovirus is given as 20 minutes. A 12-log reduction is predicted in 2.02 minutes at $60^\circ C$, but it is unclear how much extrapolation was done to reach that figure.

Van Donsel et al. [93] studied the thermal resistance of human and simian Rotaviruses. Titers were measure by plaque assay. It is not clear what holding times were used or what the final concentration was but a $D_{65}$-value of 2.5 minutes was calculated for human Rotavirus with a $z$-value of $4.33^\circ C$. In order to fit the data to the log-linear model the initial concentration data points were ignored as suggested by Block [12].

White et al. [97] studied the thermal resistance of the enterovirus Coxsackie virus B-5 (Faulkner Strain). Suspensions of tissue culture maintenance medium were sealed in capillary tubes. The initial and final titer were compared with tissue culture methods. Heating to $80^\circ C$ resulted in over a 6-log reduction in infectivity.

5.5 Protozoa

Protozoa present a special challenge to water treatment processes for three reasons: First, they form cysts that are resistant to chemical treatments. Second, they are motile and able to defeat filtering efforts. Third it only takes one organism to cause an infection in an individual[84].

Apart from Cryptosporidium there is little data on the thermal inactivation of waterborne protozoa. Other researchers that have attempted collected thermal inactivation data have also found little information for temperatures above $70^\circ C$ or holding times of one minute or less [5; 6; 60; 64; 80].

Deng and Cliver [29] studied the thermal inactivation of Cryptosporidium parvum in apple cider. 1.485 ml samples of cider were heated to $71.1^\circ C$ and then 15-$\mu m$ of oocyst stock was added, resulting in and initial concentration of $10^6$ oocysts/ml. The cider was heated for 5, 10 and 20 seconds and then immediately cooled in an ice bath.
Heating for 5 second produced a 4.8 log reduction in infectivity and heating for 10 or 20 seconds resulted in at least a 5-log reduction in infectivity.

Fayer [36] studied the thermal inactivation of Cryptosporidium parvum in water. 5-ml samples of distilled water with a oocyst concentration of $10^6$ oocysts/ml were heated in a metal block thermal DNA cycler to various temperatures. After heating for 1.25 minutes the samples were cooled and then orally inoculated into mice. Steady state temperatures were not achieved. It was found that those samples that had a temperature of at least 72.4°C at the end of heating had no infectivity in mice.

Harp et al. [42] studied the thermal inactivation of Cryptosporidium parvum in water and milk. Suspensions of water and milk with oocyst concentrations of $10^8$ per ml were processed in an Armfield FT43A Laboratory Pasteurizer at a temperature of 71.1°C for holding times of 5, 10, and 15 seconds. Samples were then orally inoculated in mice. In all cases (total of 177 mice) no infectivity was found.

Ongerth et al.[65] studied the thermal resistance of Giardia lamblia and Giardia muris. Cycst were added to water that was heated to 50°C, 60°C, and 70°C for ten minutes. Cyst viability was determined by excystation and by staining. Heating to 50°C and 60°C resulted in a 95% and a 98% reduction in viability, respectively. Heating to 70°C resulted in no detectible survivors.

Schaefer et al.[76] studied the thermal inactivation of Giardia muris. Viable cells were counted before and after heating to various temperatures for ten minutes. No viable cells were found for temperatures above 54°C.

Though no details are given and it is not clear what original work is referenced, Feachem et al.[37], report a 5-log reduction in Entamoeba histolytica in one minute.

### 5.6 Conclusion

Table 5.1 summarizes the thermal inactivation data presented in sections 5.3–5.5. Only studies that produced at least a 5-log reduction in contamination were included.
and only if final concentration values or holding times were specified.

From the published data any process that heats water to at least 65°C for two minutes and at least 80°C for more than one minute should provide a least 5-log reduction in the infectivity of *Campylobacter spp.*, *Escherichia coli*, *Salmonella spp.*, *Shigella spp.*, *Vibrio cholerae*, *Yersinia enterocolitica*, Hepatitis A, Poliovirus type 1, Coxsackie virus B-5, and *Cryptosporidium parvum*.

High temperature thermal inactivation data is needed for *Vibrio cholera*, many viruses families, particularly Rotavirus which had exhibited high thermal resistance at 65°C, and the protozoa *Entamoeba histolytica* and *Giardia spp.*

The lack of thermal inactivation data for Rotavirus is worrisome since it is believed to be the cause of 20% to 70% of all diarrhea associated hospitalizations in developing countries[67].

The effectiveness of a water treatment process depends on the makeup of the water being treated. No process can guarantee complete inactivation of all pathogens under all circumstances. The time required for a 5-log reduction was chosen as a baseline. For water with high concentrations of pathogens, the times indicated in table 5.1 may not be sufficient to eliminate the infection risk. To increase the effectiveness of the treatment, pasteurization should be combined with filtering (roughing filters and/or slow sand filtration) and proper handling of treated water to avoid recontamination[17].
### Table 5.1: Summary of Thermal Inactivation Data

<table>
<thead>
<tr>
<th>Microorganism Name</th>
<th>Suspension Media</th>
<th>Temperature (°C)</th>
<th>Time for 99.999 % Inactivation (s)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Campylobacter jejuni</em></td>
<td>Water</td>
<td>60</td>
<td>42</td>
<td>[82]</td>
</tr>
<tr>
<td><em>Campylobacter coli</em></td>
<td>Water</td>
<td>63</td>
<td>16.2†</td>
<td>[28]</td>
</tr>
<tr>
<td><em>Escherichia coli</em></td>
<td>Milk</td>
<td>63</td>
<td>16.2†</td>
<td>[28]</td>
</tr>
<tr>
<td><em>Salmonella spp.</em></td>
<td>Apple Cider</td>
<td>68.1</td>
<td>14</td>
<td>[56]</td>
</tr>
<tr>
<td><em>Shigella dysenteriae</em></td>
<td>Milk</td>
<td>76.7</td>
<td>5</td>
<td>[35]</td>
</tr>
<tr>
<td><em>Vibrio cholerae</em></td>
<td>Peptone Water</td>
<td>71</td>
<td>18</td>
<td>[78]</td>
</tr>
<tr>
<td><em>Yersinia enterocolitica</em></td>
<td>Milk</td>
<td>62</td>
<td>69</td>
<td>[82]</td>
</tr>
<tr>
<td><em>Poliovirus</em></td>
<td>Water/Milk</td>
<td>72</td>
<td>30</td>
<td>[87]</td>
</tr>
<tr>
<td><em>Hepatitis A</em></td>
<td>Skim Milk</td>
<td>80</td>
<td>35.4</td>
<td>[10]</td>
</tr>
<tr>
<td><em>Feline Calicivirus</em></td>
<td>Cockles</td>
<td>78</td>
<td>60</td>
<td>[79]</td>
</tr>
<tr>
<td><em>Entamoeba histolytica</em></td>
<td>Unknown</td>
<td>60</td>
<td>60</td>
<td>[37]</td>
</tr>
<tr>
<td><em>Cryptosporidium parvum</em></td>
<td>Water</td>
<td>72.4</td>
<td>60</td>
<td>[36]</td>
</tr>
<tr>
<td><em>Cryptosporidium parvum</em></td>
<td>Apple Cider</td>
<td>71.7</td>
<td>10</td>
<td>[29]</td>
</tr>
<tr>
<td><em>Cryptosporidium parvum</em></td>
<td>Milk</td>
<td>71.7</td>
<td>5</td>
<td>[42]</td>
</tr>
<tr>
<td><em>Cryptosporidium parvum</em></td>
<td>Water</td>
<td>71.7</td>
<td>5</td>
<td>[42]</td>
</tr>
</tbody>
</table>

†—Detection Limit Not Known, but at Least a 4-log Reduction was Achieved.
Chapter 6

Review of Solar Water Pasteurization

There are four ways in which solar energy is used to treat water that contains microbial contaminants. These methods are: distillation, UV disinfection, photochemical treatment, and pasteurization. Each of these processes is described in chapter 3. This chapter will review the current research in the area of solar water pasteurization. A review of the other methods of solar water treatment can be found in [17; 26; 39]. Pasteurization systems can be broken into three categories based on their operation. Section 6.1 reviews batch systems. Section 6.2 reviews flow-through systems that use a thermostatic valve to control flow. Section 6.3 reviews valve less flow-through systems that use the density difference between two columns of water to control flow. Section 6.4 concludes the chapter.

6.1 Batch Systems

In batch systems a fixed amount of water is placed into a container that gets heated by the sun. After the water has reached a specified temperature for an adequate amount of time it is emptied into a clean water storage vessel for later use. Batch systems typically use some form of visual indicator to signal when pasteurization is complete. One simple indicator consists of a glass tube that contains solid soybean fat. When the pasteurization temperature is reached the fat melts and flows into the
lower section of the tube[2].

One way to batch heat water is to place jugs into a solar oven. Ciochetti et al.[23] constructed a solar cooker out of an insulated cardboard box, a glass cover, and an aluminum foil reflector attached to the lid. The inner dimensions of the cooker were 0.70 m x 0.49 m x 0.35 m. Two 3.7 liter black jugs were placed inside the cooker. By adjusting the cooker so that it faced the sun every hour, water was heated from 20°C to over 68°C in six hours.

A solar puddle can also be used to batch pasteurize water. A solar puddle consists of a black absorbing layer of plastic covered by a small layer of water. A layer of clear plastic covers the water to reduce thermal and evaporative losses. Water is siphoned out of the puddle at the end of the day. Andreatta, et al. experimented with solar puddles in Berkeley, California. They found that in full sun a solar puddle with a depth of 21.5 mm reached a peak temperature of above 75°C. A 2 m by 6 m puddle can treat over 200 liters of water per day[2].

In another study reflectors were used to concentrate sunlight on glass bottles that contained water contaminated with *E. coli* and bacteriophage T2. When black bottles were used on sunny days, 1.4 liters of water reached a temperature of 70°C in 1.5 to 2 hours. Both *E. coli* and T2 were fully inactivated within 1.5 hours[73].

SUN, Inc. manufactures a batch pasteurizer that consists of a 19-liter storage tank inside an evacuated glass tube. The system generally produces one batch per sunny day. Since the system is capable of storing energy from day to day it is possible for it to produce two batches during one day. It will only produce two batches when several sunny days occur consecutively[17].

When clear containers are used, pasteurization and UV disinfection occur simultaneously. Joyce et al.[46] experimented with clear plastic 2-liter soda bottles. Water contaminated with *E. coli* was exposed to full Kenyan sunshine for at least seven hours. No viable organisms were found at the end of the day or within twelve hours
Sommer et al.\cite{81} report the findings of many laboratory and field investigations. Using plastic bags is much more effective than using glass or plastic bottles. Plastic bags transmit more UV radiation than either plastic or glass bottles. UV intensity decreases rapidly with increasing water depth. Flat plastic bags typically have a depth much less than water in bottles.

McGuigan et al.\cite{59} performed controlled experiments to determine the relationship between temperature, UV exposure, and microbe inactivation. Tests were performed on \textit{E. coli} at two turbidity levels, three temperatures and three radiation levels. The tests showed that even small levels of UV radiation could improve the pasteurization process. During an eight hour period clear water maintained at 45\degree C and exposed to 40mW/cm$^2$ of radiation experienced a 4-log reduction in viable \textit{E. coli}. Water maintained at 45\degree C for eight hours, but not exposed to light experienced almost no reduction in viable \textit{E. coli}.

Similar tests were performed by with a flat plate collector that had a UV transmittable plastic cover sheet. Rijal et al. reported 3-log reductions in the concentrations of faecal coliform, and a 4-log reduction in FRNA virus with 2-5 hour exposure to sun when the temperature of the water reached at least 60\degree C\cite{71}.

### 6.2 Flow–Through Systems with Valves

Figure 6.1 shows a schematic for a typical flow-through solar pasteurization system. Water from a contaminated supply is preheated in a heat exchanger. A solar collector then heats the water to the desired pasteurization temperature. Often a flow control valve is used to make sure the water leaving the collector is at the desired temperature. Upon leaving the collector the water enters a holding tube. The holding tube is sized to make sure the water stays at an elevated temperature for the desired time. Once the water has been pasteurized it enters the heat exchanger again to preheat the
incoming water. Treated water is collected in a reservoir for later use. Flow-through systems offer advantages over batch systems. A batch process requires a fixed amount of energy to achieve pasteurization. The amount of energy needed to raise the entire vessel to the pasteurization temperature must be collected. If slightly less energy is collected then no purified water is produced. Energy is lost if a vessel is allowed to heat beyond the pasteurization temperature before it is emptied and refilled. For batch processes to be effective one must estimate the amount of energy that will be available [2]. In a properly designed flow-through system water is treated continuously based on the amount of energy collected. The flow rate through the collector is regulated by the available energy. Another advantage of flow-through systems is that they can more easily incorporate heat exchangers to preheat untreated water with treated water. This greatly reduces the amount of solar energy needed[17].

PAX World Services produced a flow-through system that consisted of 15 to 18 meters of coiled black tubing enclosed in a glass covered solar cooker. The unit controlled flow with an automotive thermostat set to open at 83.5°C and produced 16 to 24 liters per day [2]. The tested unit did not contain a heat exchanger. A simple heat exchanger has been built and independently tested. With the heat exchanger
the PAX system is projected to produce 80-96 liters of water[2]. This projection is probably optimistic since it does not take into account the thermal capacity of the heat exchanger. The thermal mass of the heat exchanger can result in production rates much less than those predicted with a steady state model[85; 86].

Anderson et al.[1] used a parabolic trough solar concentrator to pasteurize water. The receiver of the collector consisted of three concentric pipes. Untreated water was fed into one the end of the pipe through the outer annulus. When the pasteurization temperature was achieved an automotive valve at the far end of receiver opened to allow the water to flow into the inner annulus. Solar radiation and the treated water flowing through the inner annulus simultaneously heated water in the outer annulus. This system produced 2500 liters per day with an aperture area of 28 m².

Jørgensen et al.[45] used flat plate solar collectors to pasteurize water. An adjustable thermostat valve was used to control flow. The affect of the valve set point on the inactivation of microorganisms was studied. A set point of 75°C was recommended to ensure inactivation of E. coli, Streptococcus faecalis, and Salmonella typhimurium. The collector treated about 50 l/m² per day.

A flat plate solar water pasteurizer with an integral heat exchanger was designed and tested by Stevens et al.[85; 86]. The system controlled flow with an automotive thermostat that required the water to be heated to about 75°C. After a significant warm-up period the system was capable of treating up to 55 l/(hr-m²). The large warm up period (as much as three hours) was caused by the large thermal mass of the water in the system.

Safe Water Systems produces a flat plate solar pasteurization system. The system uses a custom designed valve to pasteurize water at a temperature of 79°C. The collector has an area of 3.7 m². With a heat exchanger, the system can produce up to 95 liter per hour during steady operation and up to 760 liters per day[74]. The effectiveness of the system in destroying several microorganisms has been tested. The
system tested did not include a heat exchanger and only treated 30 liters per day. The system was able to produce over a 5-log reduction in fecal indicator bacteria as well as Salmonella and MS2 viruses[38]. A system that incorporates a heat exchanger may not provide the same results since the water would not be at an elevated temperature for the same amount of time.

Like batch systems the effectiveness of flow through pasteurization systems can be increased if they are combined with UV treatment. Sommer et al.[81] built and tested a combined solar water treatment reactor. The system heated water in a collector to about 50°C and then exposed it to solar radiation. The system has been tested and proven effective against faecal coliforms. The system produced about 100 liters of treated water per square meter of solar collector per day.

Saitoh et al. built a solar box cooker to heat water in a glass container that allowed exposure to UV radiation. The system incorporated a heat exchanger to increase throughput. The system heated water to above 70°C and produced between 8 and 10 liters of water per day for an aperture area 0.27 m²[75].

6.3 Density Driven Flow–Through Systems

In a valve-less system the flow is controlled by the density difference between a hot and cold column of water as first proposed by Boettcher et al.[13]. The operation of a density difference system relies on the fact that the density of water decreases with temperature (above 4°C). A column of warm water can be supported by a slightly shorter column of cool water. Untreated water is fed to the system from a fixed height. Water flows through the collector and then must pass through a riser tube that is slightly higher than the feed water reservoir. Flow will not occur unless the water in the riser tube is warm enough. The relative height of the water columns can be adjusted to achieve a desired outlet water temperature.

Bansal et al. [8] conducted experiments with a density driven water treatment
One experiment was conducted with evacuated tube collectors in Juelich, Germany. Another experiment was conducted with flat plate collectors in New Delhi, India. The evacuated tube collector produced about 10 liters of water per kWh of solar radiation, while the flat plate collector produced about 3.5 liters of water per kWh of solar radiation. Both collectors had an outlet temperature of about 95°C.

Cobb [24] constructed a simple pasteurization system out of a two concentric copper pipes. The outer pipe was painted black and the pipes were placed under a glazing. Water flowed from a fixed inlet reservoir through the outer pipe. When the temperature in the outer pipe reached 85°C it spilled over into the inner pipe. The system reached a maximum flow rate of about 4.2 liters per hour for a collector area of 0.56 m².

6.4 Conclusion

This chapter has presented the work other researches have done in the field of solar water pasteurization.
Chapter 7

Design Development

This chapter reviews the previous work done at Colorado State by the author and his advisor, Professor William S. Duff. The results of the preliminary experiments run with the systems described in this chapter led to the design of the valve-less flow-through water pasteurization described in chapter 8. Section 7.1 describes the experiences encountered when using a thermostatic valve to control flow in a flow-through system. Section 7.2 presents the results of a preliminary valve-less system.

7.1 Valved System

The first flow-through system built and tested contained an off-the-shelf automotive thermostat to control the flow of water [32]. In this system water flowed from an upper reservoir through a heat exchanger where it was pre-heated by hot treated water that was returning from the collector. The water then flowed through an evacuated tube solar collector where it reached its maximum temperature of about 85°C. If it was warm enough the water passed through the control valve and then flowed back through the heat exchanger and into a treated water reservoir.

The automotive thermostats used were not on/off valves. Typically they went from being fully open to fully closed over a temperature range of about 10°C. This allowed the valve to regulate the flow of water for varying sunlight conditions. If the incident radiation increased, the temperature of the water increased, and caused
the valve to become more open. This increased the flow rate of water through the collector. If the incident radiation deceased the temperature dropped and the valve closed a little to decrease the flow rate.

Though the valve was successful in controlling the temperature and flow rate of the water for several hours during a given test day, the valve was unable to control flow throughout an entire test day.

The valve had difficulty controlling the system flow, because the temperature of the water in the heat exchanger would warm up throughout the day. Early in the day, when the water in the heat exchanger was cool, the collector needed to heat the water passing through it by more than 60 C°. Later in the day, after the heat exchanger had warmed up, the collector only needed to heat the water about 10 C°. For similar solar intensities the flow rate in the afternoon needed to be about six times higher than the flow rate in the early morning. The valve could not satisfy both of these conditions.

The height/pressure of the supply reservoir was adjusted to help tune the flow of the system. When the height/pressure of the supply reservoir was too low the flow rate in the afternoon was not high enough. With too little flow the system over heated, and periodic boiling occurred as shown in figure 7.1.

Boiling is undesirable for two reasons: First, the system is not designed to retain vapor. The energy used to evaporate water is lost and this reduces the daily production of the system. Second, and most important, boiling may cause water to be pushed through the system before it has been properly heated which may lead to contamination of the treated water reservoir.

If the height/pressure of the supply reservoir was raised so that the valve could regulate flow in the afternoon, the system performed poorly at startup. At the beginning of the day the valve would start closed. As sunlight hit the collector the water inside the collector was heated. The water surrounding the valve was heated via con-
Figure 7.1: Periodic Boiling in a Valve Controlled System. The Temperature Shown Is the Temperature of the Water as It Leaves The Valve.
duction and convection currents by the water inside the collector. When the water surrounding the valve reached the set-point temperature the water in the collector was at a much higher temperature. When the valve would first open, hot water from inside the collector would begin to pass through the valve. This caused the valve to open even more and the flow rate would increase rapidly. As cool water from the heat exchanger made its way through the collector the temperature at the valve would start to drop. If the flow rate of the water was too high, the temperature would drop too quickly for the valve to respond and water that had not been properly heated would pass through the valve. Often as cooler water passed through the system the valve would completely close and the cycle would repeat several times at the beginning of the day.

Several attempts were made to find an intermediate supply reservoir height/pressure, but on all test days the system either allowed untreated water to flow in the morning or experienced boiling in the afternoon.

7.2 Simple Density-Difference Control

Because of the difficulties encountered with thermostatic valves a density driven system was built and tested[32]. Figure 7.2 shows a schematic of the system. In this system the untreated water reservoir was maintained at a height of approximately 100” (254 cm). During operation water would flow from the supply reservoir through a pipe (the collector tube) that was clamped to the condensers of five heat pipe solar collectors with a total absorber area of 0.45 m². The heated water then had to flow out of a pipe (the riser tube) that was at a height of 102 3/4” (260.9 cm). These heights were chosen because a 20°C column of water (with a density of 998.2 kg/m³) can support a column of 80°C (971.8 kg/m³) that is 1.027 times taller. The supply water could be cooler than 20°C, but even if the supply had the average density of 5°C water (1000 kg/m³) the treated water would not spill over until it has the average
Figure 7.2: A Simple Density Difference Driven Pasteurization System without a Heat Exchanger (a) and with a Heat Exchanger (b).
density of 78°C water (973 kg/m³).

The collector tube was constructed at a 45° angle in an attempt to promote natural convection in the riser tube. During testing it was found that there is virtually no natural convection within the riser tube. At the start of the day the water in the collector tube would begin to heat, but the water in the riser tube remained cool enough so that there was no flow. Eventually the water in the collector tube began to boil. The boiling process would heat the water in the riser tube and the system was able to regulate flow for the rest of the day.

As with the systems that have valves, boiling is undesirable because it may allow for untreated water to be pushed through the system. Experiments were conducted with several different riser tube diameters and even with the entire riser tube at a 45° angle, but the boiling at startup could not be eliminated.

7.3 Conclusion

This chapter has presented the preliminary solar water pasteurization research conducted at Colorado State University. Both the valved system and the valve-less system experienced boiling during operation. As mentioned, boiling is a significant problem for a solar water pasteurization system as it may result in contamination of the treated water reservoir.
Chapter 8

Design of Density Driven System with an Internal Circulation Loop

The chapter describes the current density driven solar water pasteurization system. This system incorporates an internal circulation loop that ensures the collector tube does not overheat and thus eliminates boiling. The system consists of five components: a supply reservoir, a heat exchanger, a circulation loop, a holding tube, and a treated water reservoir. Section 8.1 gives a brief overview of the system. Sections 8.2 to 8.6 give details about the individual components of the system. Section 8.7 describes how the relative heights of the elements of the system were designed to create the desired treatment temperature. Section 8.8 concludes the chapter.

8.1 Overview of System

A schematic of the system is shown in 8.1. Untreated water entered the system from an elevated reservoir. The untreated water was then pre-heated in the heat exchanger by hot treated water. The water then entered the circulation loop where it was heated by five evacuated tube heat-pipe solar collectors with a total collector area of 0.45 m². Once properly heated, water flowed over the spill-over and into the holding tube. After flowing through the holding tube the water re-entered the heat exchanger were it was cooled before entering the treated water reservoir. To reach the treated water reservoir the water had to pass over a secondary spill-over point.
Figure 8.1: Schematic of Density Driven System with an Internal Circulation Loop (Numbers Indicate Thermocouple Locations).
Without the secondary spill-over point there would have been no way to keep water in the heat exchanger or the holding tube. (Note that both spill-over points were vented. This ensured that water was not siphoned through the system.)

8.2 Untreated Water Reservoir

Tap water was supplied to a plastic container that served as the elevated supply reservoir. A solenoid valve controlled the water flow to the container. Two signal wires were attached to the container. One was secured on the bottom of the container and one was secured to the wall of the container. The electrical resistance between the two signal wires was used to control the solenoid valve. When the water level dropped below the signal wire attached to the side of the container the electrical resistance became very large and the valve was turned on. When the water level reached the signal wire on the side of the container the resistance dropped and the valve was turned off. By this method the water level in the supply reservoir was maintained to within 0.25 cm of the location of the upper control wire.

8.3 Heat Exchanger

The heat exchanger used was a single pass shell and tube set up in a counter flow arrangement. To limit thermal losses, the hot treated water from the holding tube entered the tube side and the cool water from the supply reservoir entered the shell side of the heat exchanger. Untreated water left the shell side of the heat exchanger and flowed into the circulation loop. As shown in figure 8.1, to encourage stratification

The unit contained 68, 16”, copper tubes with an inner diameter of 1/4” and an outer diameter of 5/16”. The shell was cast iron with an inner diameter of 3.5”. The shell was surrounded by at least 3” of extruded polystyrene on all sides.
Figure 8.2: Schematic of the Circulation Loop.
8.4 Circulation Loop

The circulation loop consisted of the ‘collector tube’, the ‘riser tube’ and the ‘convection tube’. As shown in figure 8.2, water from the heat exchanger entered the circulation loop in the convection tube 8” above the collector tube. The convection tube was connected to the riser tube 49” above the collector tube. Properly heated water left the circulation loop and entered the holding tube via the spill-over located 52” above the collector tube.

Within the circulation loop no tubes were oriented horizontally. All tubes were slightly sloped towards the riser tube. This was done in an attempt to make sure that no vapor would collect in the system and all vapor bubbles would leave the system through the vent at the top of the riser tube. The vent also ensured that water was not siphoned through the system.

The riser tube and the convection tube were both made from nominal 1/2” type M copper pipe, while the collector tube was made from nominal 3/4” type M diameter copper pipe. The circulation loop was sandwiched between two 2.5” layers of extruded polyurethane. As shown in figure 8.3, the five evacuated tube heat-pipe solar collectors were clamped to the ‘collector tube’ by aluminum heat exchange blocks. Heat transfer grease was used to reduce the contract resistance between the heat-pipe and the aluminum blocks, and between the aluminum blocks and the collector tube. The aluminum blocks were surrounded by at least 3” of extruded polyurethane.

8.5 Holding Tube

From preliminary experiments the expected peak flow of the system was 25 kg/hr. The size of the holding tube was based on a flow rate of 30 kg/hr and a minimum holding time of one minute.

For water at 85°C (ρ=968.1 kg/m³) a mass flow rate of 30 kg/hr results in a volumetric flow rate 0.516 liters/min. Based on slug flow conditions a holding time of
Figure 8.3: Aluminum Blocks Conduct the Energy From the Condenser of the Heat–Pipe to the Collector Tube.
Figure 8.4: Schematic of Holding Tube
one minute requires a holding tube with volume of 0.516 liters. For water flowing in a circular pipe the centerline velocity is at most twice the bulk velocity of the fluid. This means that the actual holding time will be at least half the holding time for slug flow conditions. The holding tube was designed to have a volume of 1.2 liters.

Nominal 1/2” copper pipe was chosen since it is the smallest standard size for which fittings are readily available. A small diameter holding tube is desirable because the smaller the tube, the larger the bulk velocity. A larger bulk velocity reduces the effects of diffusion and microorganism motility. Type-M pipe with an inner diameter of 1.45 cm was used. To have a volume of 1.2 liters, 7.3 meters (24 ft) of tube were required.

The holding tube consisted of ten 2-ft sections of copper tube connected in an S-pattern. As shown in 8.4 all the tubes were sloped above horizontal. This ensured that no air or vapor bubbles collect in the holding tube. Including the S-bends the holding tube had a total measured volume of 1.3 liters. The holding tube was sandwiched between 2 2.5”- layers of extruded polystyrene.

Based on the expected flow and the pipe geometry, the Reynolds number and entry length were calculated with equations 8.1 and 8.2, respectively[20].

\[
Re = \frac{4\dot{m}}{\mu \pi D} \quad (8.1)
\]

\[
L_h \approx 0.05 Re D \quad (8.2)
\]

For the design conditions equations 8.1 and 8.2 resulted in a Reynolds number of 2200 and an entry length of 1.6 meters (5.2 ft). Fully developed laminar flow was expected at the outlet of the holding tube[20]. The calculated flow rate was close to the predicted transition region for flow in a pipe. If there were to be turbulence, the flow profile would be broader and the centerline velocity would be lower, resulting in a longer minimum holding time.
8.6 Treated Water Reservoir

After being used to pre-heat untreated water, the treated water leaving the heat exchanger had to pass over a secondary spill-over tube that was 5” lower than the spill-over point at the top of the riser tube (see 8.1). The secondary spill-over tube ensured that the tube-side of the heat exchanger and the holding tube had water in them. After passing over the secondary spill-over tube the water entered the treated water reservoir where it was weighed.

8.7 Design of the Supply Reservoir Height

Figure 8.5 shows the relative heights of the supply reservoir, the spill-over point, the collector tube, the inlet of the circulation loop, the exit of the shell side of the heat exchanger, and the inlet of the shell side of the heat exchanger. These relative heights determined the operating conditions of the system.

The entire system was mounted on a wooden platform. In order to provide clearance for pipe connected to the bottom of the tube side of the heat exchanger, the inlet of the shell side of the heat exchanger needed to be 8” above the platform. The spacing between the inlet and exit of the shell side of the heat exchanger was 16”. To provide enough tilt to the collectors, the collector tube was located 18” above the platform. In an attempt to ensure that no air or vapor collected between the heat exchanger and the circulation loop, the inlet to the circulation loop was set 2” higher than exit of the heat exchanger (the inlet to the circulation loop was 8” higher than the collector tube).

The thermal expansion of water is what drives the flow in a density difference system. Figure 8.6 shows the density of water as a function of temperature. The operating temperature of a density difference driven system is predominately based on the ratio the supply and spill-over heights. Since it is the ratio of the heights that determines the temperature, the greater the heights the less precision is needed.
Figure 8.5: Elevation Schematic of System
Figure 8.6: Density of Water as a function of Temperature
to ensure the desired operating temperature. The spill-over height of 52” above the collector tube produced adequate precision while keeping the overall size of the system reasonable.

The relative height of the supply reservoir was selected by considering the pressure balance between a ‘warm’ and ‘cold’ column of water. The ‘cold’ column consisted of the water flowing from the top of the supply reservoir to the inlet of the shell side of the collector. The ‘warm’ column consisted of the water flowing from the spill-over point to the inlet of the shell side of the heat exchanger, including the water in the circulation loop and the water in the shell side of the heat exchanger.

To simplify the height design process a few assumptions were made. It was assumed that the system was well insulated and that the entire ‘cold’ water column was at a uniform temperature. The temperature of the water in the heat exchanger was assumed to vary nearly linearly with height and the average density of water in the heat exchanger was assumed to be the density of the average temperature. The temperature in the circulation loop was assumed to be uniform. Because of the relatively slow flow rates, friction and momentum effects were ignored and near static conditions were assumed to hold throughout the system.

Equation 8.3 was used to determine the pressure difference between any two points in the system.

$$\Delta P = -\rho_{\text{ave}} g \Delta h$$

Using equation 8.3, the pressure at the entrance of the heat exchanger was determined by thinking of it as the bottom of the ‘cold’ column.

$$P_{X_{in}} = P_{atm} + \rho (T_{\text{Supply}}) g (h_{\text{Supply}} - h_{X_{in}})$$

The same pressure was also found by treating the location as the bottom of the ‘warm’
\[ P_{X_{in}} = P_{atm} + \rho(T_{Loop}) g (h_{Spill} - h_{Loop_{in}}) \]
\[ + \rho(T_{Loop_{in}}) g (h_{Loop_{in}} - h_{X_{out}}) \]
\[ + \rho \left( \frac{T_{X_{out}} + T_{X_{in}}}{2} \right) g (h_{X_{out}} - h_{X_{in}}) \]  \hspace{1cm} (8.5)

The desired process temperature was 80°C. To build in a safety margin and allow for fluctuations in the supply reservoir height, the system was designed for an 85°C process temperature.

From preliminary experiments it was expected that, after a significant warm up period, the water leaving the shell side of the heat exchanger would be 10°C below the process temperature. For the designed process temperature of 85°C and a supply temperature of 20°C equations 8.4 and 8.6 were combined with the known heights to find the needed supply reservoir height. Note from figure 8.6 the density of water does not change much below 20°C, so the system is fairly insensitive to the supply water temperatures.

\[ h_{Supply} - h_{X_{in}} = \frac{\rho(85°C)}{\rho(20°C)} (h_{Spill} - h_{Loop_{in}}) \]
\[ + \frac{\rho(75°C)}{\rho(20°C)} (h_{Loop_{in}} - h_{X_{out}}) \]
\[ + \frac{\rho(47.5°C)}{\rho(20°C)} (h_{X_{out}} - h_{X_{in}}) \]  \hspace{1cm} (8.6)

Upon evaluation,

\[ h_{Supply} - h_{X_{in}} = \frac{\rho(85°C)}{\rho(20°C)} (44") + \frac{\rho(75°C)}{\rho(20°C)} (4") + \frac{\rho(47.5°C)}{\rho(20°C)} (16") \]
\[ = 60.5" \]

\[ h_{Spill} - h_{Supply} = 1.5" \approx 3.8 cm \]

Performing the same calculations for a temperature set point of 80°C and 90°C resulted in supply reservoir heights that were 0.25" (0.63 cm) higher, and 0.15" (0.37 cm) lower than the 85°C height, respectively.
To calculate the spill-over conditions at the start of a test day (e.g. before the heat exchanger has warmed up), the water in the heat exchanger, and the tube connecting the heat exchanger to the circulation loop, were assumed to be at the supply water temperature. The start-up spill-over temperature can be found with equation 8.7.

\[
\rho (T_{\text{Spill}}) = \rho (T_{\text{Supply}}) \left( \frac{h_{\text{Supply}} - h_{\text{Loop,in}}}{h_{\text{Spill}} - h_{\text{Loop,in}}} \right)
\]  (8.7)

Upon evaluation,

\[
\rho (T_{\text{Spill}}) = 998 \text{ kg/m}^3 \left( \frac{42.5''}{44''} \right) \\
= 963.8 \text{ kg/m}^3 \Rightarrow T_{\text{Spill}} \approx 92^\circ C
\]

So at the beginning of the day the circulation loop should need to reach a temperature of approximately 92°C before flow begins and later in the day when the heat exchanger is fully warmed up the spill-over temperature should drop to approximately 85°C. All other operating conditions should result in a spill-over temperature between these bounds.

8.8 Conclusion

This chapter has presented a passive flow-through valve-less water treatment system that is designed to treat water to a temperature of at least 80°C for a holding time of at least one minute. This design represents an improvement over previous designs in that it eliminates boiling.
Chapter 9

Experimental Results and Discussion

The system described in Chapter 8 was tested for a total of 55 days in Fort Collins, Colorado (Latitude=40.5° Longitude=105°) from August 3rd, 2004 to October 28th, 2004. This chapter presents and analyzes the data from the test days. Section 9.1 describes the instrumentation and testing procedure. Section 9.2 presents the daily production data and analyzes the overall performance of the system. Section 9.3 presents the temperature and flow profiles for selected test days and the analysis of the performance of the individual system components. Section 9.4 concludes the chapter.

9.1 Experimental Setup and Instrumentation

The system was set up such that the collectors were oriented with a slope of 15° and a surface azimuth angle of 0°. The solar flux incident on the collectors was measured with an Eppley PSP pyranometer placed adjacent to the collectors with the same slope and azimuth angle. T-type thermocouples were used to measure temperature. The thermocouple locations are shown in figure 8.1. Three thermocouples were placed at each location and their readings were averaged. The thermocouples were placed as close to the center of flow as possible. A strain gage was placed under the treated water reservoir to monitor production and calculate the flow rate. In addition, the
treated water reservoir was weighed at the start and end of each day. The strain
gage was calibrated by weighing the treated water reservoir with different amounts
of water and recording the voltage produced by the strain gage. Figure 9.1 shows the
calibration data for the strain gage.

9.2 Daily Production

The daily production data is shown in table 9.1 and figure 9.2. The radiation values
listed on table 9.1 and the insolation values in figure 9.2 are the daily totals incident
on the collector surface.

Figure 9.2 shows that a minimum total daily isolation of about 12 MJ/m$^2$ is
required before any treated water is produced. This phenomenon is common in solar
applications. A minimum amount of energy is required to overcome losses before
energy can be delivered to the process. Roughly 7.8 kg of treated water are produced
for every MJ above 5.4 MJ.

The performance can also be expressed as a COP. It takes about 0.25 MJ to heat
one kilogram of water from 20°C to 80°C. Dividing the total daily radiation by 0.25
MJ gives the maximum production system without a heat exchanger. The COP is
the ratio of the actual production to the maximum production of a direct system.
Figure 9.3 shows the system COP as a function of total daily insolation.

9.3 Component Performance

This section analyzes the performance of the individual components of the system.
Two test days are used as examples in this analysis. The first test day (September
25th, 2004) was a mostly sunny day with a brief period of clouds in the afternoon.
The total radiation incident on the collector surface was 10.6 MJ and the system
produced 82 kg of treated water. The second test day (October 18th, 2004) was
mostly cloudy in the afternoon. The total radiation incident on the collector was 8.5
Figure 9.1: Mass in Treated Water Reservoir as a Function of Strain Gage Output.
Table 9.1: Daily Production Data.

<table>
<thead>
<tr>
<th>Date (2004)</th>
<th>Daily Radiation (MJ)</th>
<th>Daily Production (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Aug</td>
<td>5.9</td>
<td>12</td>
</tr>
<tr>
<td>4-Aug</td>
<td>10.7</td>
<td>99</td>
</tr>
<tr>
<td>5-Aug</td>
<td>9.3</td>
<td>69</td>
</tr>
<tr>
<td>10-Aug</td>
<td>9.0</td>
<td>72</td>
</tr>
<tr>
<td>11-Aug</td>
<td>13.1</td>
<td>152</td>
</tr>
<tr>
<td>13-Aug</td>
<td>12.9</td>
<td>147</td>
</tr>
<tr>
<td>14-Aug</td>
<td>12.8</td>
<td>138</td>
</tr>
<tr>
<td>15-Aug</td>
<td>12.5</td>
<td>131</td>
</tr>
<tr>
<td>16-Aug</td>
<td>12.5</td>
<td>128</td>
</tr>
<tr>
<td>17-Aug</td>
<td>7.8</td>
<td>65</td>
</tr>
<tr>
<td>24-Aug</td>
<td>6.2</td>
<td>21</td>
</tr>
<tr>
<td>26-Aug</td>
<td>7.0</td>
<td>23</td>
</tr>
<tr>
<td>10-Sep</td>
<td>5.9</td>
<td>33</td>
</tr>
<tr>
<td>11-Sep</td>
<td>11.9</td>
<td>101</td>
</tr>
<tr>
<td>12-Sep</td>
<td>4.0</td>
<td>1</td>
</tr>
<tr>
<td>13-Sep</td>
<td>6.0</td>
<td>8</td>
</tr>
<tr>
<td>14-Sep</td>
<td>7.4</td>
<td>10</td>
</tr>
<tr>
<td>15-Sep</td>
<td>12.0</td>
<td>74</td>
</tr>
<tr>
<td>16-Sep</td>
<td>10.4</td>
<td>89</td>
</tr>
<tr>
<td>17-Sep</td>
<td>11.5</td>
<td>89</td>
</tr>
<tr>
<td>18-Sep</td>
<td>9.6</td>
<td>71</td>
</tr>
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<td>19-Sep</td>
<td>4.9</td>
<td>7</td>
</tr>
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<td>47</td>
</tr>
<tr>
<td>23-Sep</td>
<td>11.6</td>
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</tr>
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<td>82</td>
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<td>6-Oct</td>
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<tr>
<td>7-Oct</td>
<td>10.2</td>
<td>103</td>
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<tr>
<td>8-Oct</td>
<td>10.7</td>
<td>68</td>
</tr>
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<td>10-Oct</td>
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<tr>
<td>11-Oct</td>
<td>9.0</td>
<td>10</td>
</tr>
<tr>
<td>12-Oct</td>
<td>9.9</td>
<td>92</td>
</tr>
<tr>
<td>13-Oct</td>
<td>10.4</td>
<td>78</td>
</tr>
<tr>
<td>14-Oct</td>
<td>6.2</td>
<td>6</td>
</tr>
<tr>
<td>15-Oct</td>
<td>1.3</td>
<td>1</td>
</tr>
<tr>
<td>16-Oct</td>
<td>9.3</td>
<td>31</td>
</tr>
<tr>
<td>17-Oct</td>
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<td>1</td>
</tr>
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<td>38</td>
</tr>
<tr>
<td>19-Oct</td>
<td>3.5</td>
<td>0</td>
</tr>
<tr>
<td>20-Oct</td>
<td>8.0</td>
<td>16</td>
</tr>
<tr>
<td>21-Oct</td>
<td>8.5</td>
<td>48</td>
</tr>
<tr>
<td>22-Oct</td>
<td>3.5</td>
<td>1</td>
</tr>
<tr>
<td>24-Oct</td>
<td>3.7</td>
<td>1</td>
</tr>
<tr>
<td>25-Oct</td>
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<td>24</td>
</tr>
<tr>
<td>26-Oct</td>
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<td>32</td>
</tr>
<tr>
<td>27-Oct</td>
<td>5.4</td>
<td>3</td>
</tr>
<tr>
<td>28-Oct</td>
<td>8.7</td>
<td>47</td>
</tr>
</tbody>
</table>
Figure 9.2: Normalized Production as a Function of Total Daily Insolation on the Collector Surface.
Figure 9.3: System COP as a Function of Daily Insolation on the Collector Surface.
MJ and the system produced 38 kg of treated water.

Figure 9.4 and figure 9.5 show the irradiance, the temperature at the top of the circulation loop (thermocouple location 6 on figure 8.1), and flow rate for September 25th 2004, and October 18th 2004, respectively.

On September 25th 2004, the water in the circulation loop reached a temperature of just under $88^\circ C$ before flow started. As the day progressed and the temperature in the heat exchanger increased (see figure 9.7), the operating temperature dropped to approximately $83^\circ C$. A brief period of clouds caused the circulation loop temperature to drop and the flow through the system stopped. When the clouds left the circulation loop warmed up to about $81^\circ C$ and flow continued. Though the system regulated the operating temperature well throughout most of the day, sharp dips in the circulation loop temperature occurred periodically. These temperature dips were noted on many test days. The temperature dips are typically preceded by a sharp increase in flow rate, the flow rate then drops as the circulation loop warms back up to the operating temperature.

The exact cause of the temperature drops is not known, but it is believed that vapor accumulation is to blame. It is possible that vapor collects in one or more locations within the circulation loop or the heat exchanger. Once a vapor bubble is large enough, it begins to move and it makes its way to the vent in the top of the riser tube. As the bubble leaves the circulation loop, water from the heat exchanger quickly takes its place causing the temperature of the circulation loop to drop.

Regardless of the cause, these dips in temperature are worrisome since they represent periods of time in which the water that flows into the holding tube is below the desired process temperature.

On October 18th 2004, the water in the circulation loop again reached a temperature of approximately $87^\circ C$ before flow started. As the day progressed the operating temperature dropped to about $82^\circ C$. Afternoon clouds caused the flow in the system
Figure 9.4: Irradiance, Circulation Loop Temperature, and Flow Rate Profiles for September 25th, 2004.
Figure 9.5: Irradiance, Circulation Loop Temperature, and Flow Rate Profiles for October 18th, 2004.
to stop for two 45 minute periods. The system did not experience sharp temperature drops. If vapor bubbles are the cause of the temperature drops, it is possible that the low irradiance resulted in slow vapor bubble formation.

### 9.3.1 Circulation loop

There are three thermocouples located within the circulation loop: one on either side of the collector tube and one at the top of the loop. (See figure 8.1). Figure 9.6 shows the three circulation loop temperatures as the system warms up on September 25th, 2004. The convection tube successfully circulates water through the collector tube and riser tube, and thus eliminates boiling at start up.

### 9.3.2 Performance of the Heat Exchanger

Figures 9.7 and 9.8 show the temperature of treated water entering the tube side of the heat exchanger (thermocouple location 12 on figure 8.1), the temperature of pre–heated water leaving the shell side of the heat exchanger (thermocouple location 2 on figure 8.1), the irradiance of the collector surface, and the flow rate through the system for September 25th, 2004 and October 18th, 2004, respectively.

On September 25th, 2004 it took about 2.5 hours of full sun after system flow started for the heat exchanger to reach its steady operating temperature of approximately $72^\circ$C. On October 18th, 2004 clouds moved in just as the heat exchanger was reaching its steady operating temperature. After the clouds cleared the heat exchanger needed to be warmed up again, resulting in a low daily production.

Since the heat exchanger is not perfectly insulated the hot–side effectiveness is not the same as the cold–side effectiveness. It is the cold–side effectiveness that contributes to the performance of the system. Assuming constant specific heats and since the flow rate for the hot and cold side of the heat exchanger are equal the
Figure 9.6: Circulation Loop Temperatures During Start–Up on September 25th 2004.
Figure 9.7: Irradiance, Temperature of Heat Exchanger Hot–Side Inlet, Temperature of Heat Exchanger Cold–Side Outlet, and Flow Rate Profiles for September 25th 2004.
Figure 9.8: Irradiance, Temperature of Heat Exchanger Hot–Side Inlet, Temperature of Heat Exchanger Cold–Side Outlet, and Flow Rate Profiles for October 18th, 2004.
instantaneous cold–side effectiveness can be found with equation 9.1.

\[
\varepsilon_{Cold} = \frac{(T_{Cold_{out}} - T_{Cold_{in}})}{(T_{Hot_{in}} - T_{Cold_{in}})}
\]  

(9.1)

The instantaneous cold–side effectiveness for September 25th, 2004, and October 18th, 2004 are shown in figure 9.9. The instantaneous calculations are meaningless when the flow rate or temperatures are varying significantly. During steady operation the effectiveness of the heat exchanger was about 0.85 on both test days.

### 9.3.3 Temperature Profile Within the Holding Tube

Figures 9.10 and 9.11 show irradiance and the daily temperature profiles for inlet (thermocouple location 11 on figure 8.1) and outlet (thermocouple location 8 on figure 8.1) of the holding tube for September 25th, 2004 and October 18th, 2004, respectively. When water is flowing there is little temperature drop within the holding tube. Both temperatures in the holding tube experienced sharp drops on September 25th, indicating that the temperature fluctuations in the circulation loop affect the water entering the holding tube.

As water flows through the holding tube its temperature drops. The temperature of the water as it leaves the holding tube is the minimum temperature it has had in the holding tube, thus the holding tube outlet temperature represents the minimum holding temperature of the process. Since the volume of the holding tube is known, the holding time at a particular time of day can be calculated by integrating the mass flow rate backwards through time. In this way it is possible to determine when the water that is currently leaving the holding tube entered the holding tube. To take into account the possibility of a high centerline velocity the holding time determined with this method should be multiplied by a factor of 0.5.

Figures 9.12 and 9.13 show the temperature and holding time data for the system on September 25th, 2004, and October 18, 2004, respectively. Since they correspond to periods of reduced flow, the temperature drops experienced in the circulation loop
Figure 9.9: Instantaneous Effectiveness of The Heat Exchanger on September 25th, 2004 and on October 18th, 2004.
Figure 9.10: Holding Tube Inlet and Outlet Temperature Profiles for September 25th, 2004
Figure 9.11: Holding Tube Inlet and Outlet Temperature Profiles for October 18th, 2004
do not appear to have affected the overall process of the system. The data plotted on figures 9.12 and 9.13 should not be thought of as the profile of a time varying process like the example processes ‘Process D’ and ‘Process E’ of section 4.2.1. The data is actually a collection of many constant temperature processes (like processes ‘A’, ‘B’, and ‘C’ of section 4.2.1). It is not enough for part of this data to have an acceptable holding time and temperature. In order for the process to be effective every data point needs to be above and the the right of the required inactivation level.

Figure 9.14 shows the thermal inactivation data for the pathogens on table 5.1 along with the system’s process data for for all test days. From this figure it is clear that the system should provide significant protection for those pathogens where sufficient thermal inactivation data is available. Unfortunately, as stated in section 5.6, there is not adequate thermal inactivation data for some important pathogens.

9.4 Conclusion

This chapter has presented the experimental results for a passive valve–less flow–through water pasteurization system. Not only does the system produce significant amounts of treated water, the treatment process operates at higher temperatures and for longer times than the inactivation studies reported in Chapter 5. Though the sharp dips in the temperature of the circulation loop do not seem to have adversely affected the treatment process, their occurrence is troubling and their cause should be investigated further. Though adequate thermal inactivation information does not exist for some some important pathogens, there is no data to suggest that the process in will not be viable.
Figure 9.12: Holding Tube Outlet Temperature as a function of Holding Time on September 25th, 2004
Figure 9.13: Holding Tube Outlet Temperature as a function of Holding Time on October 18th, 2004
Figure 9.14: Process and Microorganism Time-Temperature Data. The Process should be effective against all the microorganisms listed in table 5.1 (shown with circles).
Chapter 10

Possible Future Research and Conclusion

Though this thesis represents a significant amount of research there are still many opportunities for continued research. Section 10.1 presents some areas of possible research. Section 10.2 concludes the thesis.

10.1 Possible Future Research

Currently there is not a lot of information about the high temperature thermal inactivation of waterborne pathogens. There is no data about the thermal inactivation of many viruses and virus families. In particular, there is a need for high temperature inactivation data for Rotavirus. Rotavirus is believed to be responsible for a large percentage of water related sickness and it has shown high resistance to inactivation at 65°C.

The system described in this thesis has not been tested with live pathogens. Before further development of a prototype, pathogen testing should be done to ensure the system is as effective as it is thought to be.

The current system uses an off-the-shelf high effectiveness heat exchanger. The draw back of this heat exchanger is that has a large thermal mass and it takes a long time to warm up. The design of the heat exchanger could be improved. Because the flow in the system is so low, the heat transfer in the heat exchanger is dominated by
conduction rather than convection. A properly designed heat exchanger would have a very large ratio of heat transfer area to fluid volume. For a given heat exchanger design, increasing the effectiveness requires and increase in the fluid volume and thus the thermal mass. The trade-off between steady-state effectiveness and warm-up time could be studied.

The current method used to maintain the supply reservoir height relies on the active control of a solenoid valve. Preliminary experiments were also conducted with an off-the-shelf toilet float valve. The float valve performed well, but would periodically stick. The design and implementation of a reliable float valve is needed before the system can be used in remote areas.

The system described in this thesis represents a proof of concept. Future designs should focus on manufacturability and maintainability as well as shipping and installation considerations.

10.2 Conclusion

This thesis has presented the design and experimental results of a passive, density difference driven, flow-through solar water pasteurization system. The system is capable of producing 150 liters of treated water during a sunny summer day with a collector area of 0.45 m². From the analysis of the daily temperature profiles, the system should provide significant protection against most (and potentially all) common waterborne pathogens. The system represents a significant improvement over previous systems since it does not experience boiling.
REFERENCES


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