Renewable Energy 81 (2015) 795–803

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Continuous flow solar thermal pasteurization of drinking water: Methods, devices, microbiology, and analysis

J.P. Abraham [a, *], B.D. Plourde [a], W.J. Minkowycz [b]

[a] University of St. Thomas, School of Engineering, 2115 Summit Ave, St. Paul, MN 55105-1079, USA
[b] University of Illinois, Chicago, Department of Mechanical and Industrial Engineering, 2039 Engineering Research Facility, 842 W. Taylor St., Chicago, IL 60607, USA

ARTICLE INFO

Article history:
Received 24 July 2014
Accepted 31 March 2015
Available online

Keywords:
Thermal pasteurization
Solar concentration
Clean water
Renewable energy

ABSTRACT

The ability to simply and robustly pasteurize drinking water would present tremendous worldwide human health benefits. Ingestion of unsafe drinking water is a leading cause of sickness and death in the developing world. A simple method to use concentrated solar power is presented here with two complimentary numerical models. The first model allows a prediction of water temperatures within the concentrator and enables a user to vary operating parameters to assess the impact on the temperatures. The second model relates the temperatures to pathogen inactivation kinetics so that predictions of pathogen populations can be made. It is found that with a modest size system that includes a parabolic trough concentrator, a thermally activated valve, and a fluid-to-fluid heat exchanger, near complete pathogen inactivation can be achieved. Comparisons are made between simulated and experimentally determined temperatures. The comparison demonstrates the veracity of the model.

1. Introduction

Ingestion of pathogens through drinking water is a significant global health risk particularly in the developing world. Hundreds of millions of people currently do not have access to clean water [1]. In particular, children face health risks from water-borne pathogens which cause large-scale world-wide deaths [2,3]. To deal with this issue, a variety of approaches have been taken to inactivate pathogens and make otherwise unsafe water potable. With an estimated 28 billion diarrheal episodes each year [4], the social and human health costs are large.

In the past, review articles have been written which discuss the general guidelines of water treatment. On the other hand, to the best knowledge of the authors, there are no comprehensive presentations which bring together a discussion of pasteurization methodology, descriptions of devices, microbiology, and thermal analysis. It is therefore the purpose of this article to provide such a comprehensive discussion with updates from recent literature. The focus of the discussion will be on water treatment methods for developing-world applications. Specifically, attention will be given to a thermal model of a parabolic flow-through system which allows a determination of the pathogen inactivation rate. The simple model described here can be implemented using standard desktop computer resources.

The type of pathogen found in a particular water source is dictated by geography, sanitation, and nearby human activity. The pathogens are often subdivided into broad biological classes of worms, protozoa, bacteria, and viruses (ordered by decreasing size) [5]. A list of the most common water borne pathogens is provided in Table 1 which is extracted from Ref. [4].

In some resources such as [5], maps showing the presence of certain pathogens are found which allow water-resource managers to identify key health risks for a particular water treatment method. While the present manuscript presents a short review of non-thermal treatment methods, the main emphasis on thermal pasteurization will be presented so that users can tailor a thermal protocol for any pathogen which may be present in the water.

2. Issues associated with water treatment

The principle means of infestation of water is through the fecal–oral cycle. The pathogen source may be human or animal excrement, and the likelihood of contamination depends on the source of water. Typically, deeper water sources are more likely to

* Corresponding author.
E-mail address: jpabraham@stthomas.edu (J.P. Abraham).

http://dx.doi.org/10.1016/j.renene.2015.03.086

Table 1
Common water-borne pathogens.

Pathogen type	Health impact	Infective dose
Bacteria	High	Moderate
Campylobacter jejuni C. coli	High	High
Escherichia coli	High	High
Salmonella typhi	High	Moderate
Shigella spp.	High	Moderate
Vibrio cholera	High	High
Yersinia enterocolitica	High	High
Viruses		
Adenovirus	High	Low
Enterovirus	High	Low
Hepatitis A	High	Low
Enterically transmitted hepatitis	High	Low
Norwalk virus	High	Low
Rotavirus	High	Moderate
Protozoa		
Entamoeba histolytica	High	Low
Giardia intestinalis	High	Low
Cryptosporidium parvum	High	Low
Worms		
Dracunculus medinensis	High	Low

be potable. Particularly safe are deep boreholes, springs, or sealed wells. On the other hand, shallow wells and surface waters tend to present higher pathogen populations.

Prior to a discussion of water treatment methods, it is important to recognize that pathogen contamination is different from water turbidity. Turbidity refers to the optical qualities of water; low turbidity is associated with clear water whereas high turbidity characterizes cloudy or nearly opaque water. Often quantified by nephelometric turbidity units (NTU), regional or national standards give some guidance regarding acceptable levels. In industrialized nations, NTU values in the 1–5 range are found whereas streams, lakes, and other surface waters may naturally present NTU values over 1000.

Causes of high turbidity include the suspension of particulates including clay, silt, and organic matter that may not be a direct health threat but are nevertheless a concern for water safety. Particulates provide reservoirs which can house pathogens and promote pathogen growth. Furthermore, turbidity can inhibit water treatment protocols.

The most common approaches to render water safe include improved sanitation, chemical, ultraviolet, thermal pasteurization, and filtering. Each method presents both strengths and weaknesses. Optimally, multiple methods are used together to provide some degree of safety.

Perhaps most important is breaking the fecal–oral cycle by providing adequate separation between water and the contaminant. Another important step is to avoid recontamination of otherwise potable water through contact with hands, kitchen utensils, or other materials which may transmit pathogens. The aforementioned water treatment methods will be discussed briefly and interested readers are directed to references [2,4] for a more in-depth discussion. Because the primary focus of this manuscript is on thermal pasteurization, a much more detailed investigation of that technique will be given.

2.1. Slow sand filters

Perhaps the first large-scale filter method to be employed was the slow sand method (it is also a very commonly used method currently in the developing world and in remote locations). It involves the construction of a sand filter bed atop a gravel substrate. As water travels vertically through the sand, a biological layer is formed (termed schmutzdecke) which becomes the barrier for pathogens. The biological layer must be periodically removed and then regrown when hydraulic resistance increases – thereby reducing flowrates. One benefit of the slow sand filter is that it reduces turbidity as well as pathogen count. While the operation of a slow sand filter is not complex, the large area requirements and the slow flowrates are detractions. Filters may clog rapidly if the source contains high levels of particulates. Also the need for large planform area is a limiting feature [6].

Among the types of pathogens to be removed, viruses (because of their small size) are most resistant to filtering. Another issue that must be considered with filtering and other water treatment methods is that residual pathogen populations can regenerate over time so that otherwise safe levels can regain their ability to cause health risks. For instance, in some environments, bacteria can double three times per hour [2]. On the other hand, such ideal environments are unlikely to be found in practice and depending on the storage method, bacterial counts can continue to fall after the completion of filtering [2,5].

2.2. Rapid sand filters

As an alternative to slow filtering with small pore beds, larger pore sand beds can allow faster flow of water in a rapid sand filter (sometimes termed rough filtering). The larger pores allow removal of suspended particulates but their ability to remove pathogens is limited. As with slow sand filters, these devices clog quickly if the source water contains high levels of suspended particles. Also, rapid filters must be periodically cleaned by a process called backwashing which is a purposeful reversal of flow through the system.

In some cases, rapid sand filters are used to pretreat water which then flows through a slow-sand filtration system. Alternatively, rapid filters can be used in conjunction with chemical or ultraviolet treatments. Rapid filtration alone is insufficient to create potable water, but it is useful removing large suspended particles so that further treatments are more effective.

2.3. Chemical treatments

Worldwide, the most common water treatment method is chemical and chlorine is the most popular chemical. In industrial plants, automatic dosing is performed with mechanized equipment. In rural and under-developed locations, it is common for dry bleach powder to be added to water in a batch process. Regardless of the chemical application, it is essential to accurately measure the chemical application to ensure thorough treatment. Protocols have been developed for various pathogens and time-dosage criteria are available [2].

Chemical treatments have a number of advantages. In particular, when proper dosing is used, it is highly effective. Furthermore, the chemicals reside in the water after treatment and thereby inhibit a reconstitution of pathogen populations. In fact, of the treatment methods discussed in this paper, chemical means are the only method which provides resistance to recontamination.

Despite these advantages, there are also concerns with chemical treatment. First, turbidity makes chemicals less effective – high turbidity, pH, or temperature results in increases of chemical dose (by factors of 10 for moderate changes to turbidity, pH and temperature). Secondly, careful measurement of dose is required to ensure proper treatment. In small-scale batch processes, it may be difficult to ensure continued proper measurement. Finally, access to chemicals is required and the chemicals have a relatively short shelf-life which causes a reduction in effectiveness over time. An excellent review of chemical treatments can be found in Ref. [2].