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Research Paper

Energy-efficient *Legionella* control that mimics nature and an open-source computational model to aid system design

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HIGHLIGHTS

- A design for efficient *Legionella* control and general pasteurization is introduced.
- A freely-available design model developed in Microsoft Excel is described.
- Model results are compared to experimental measurements.
- Applications to *Legionella* control and solar disinfection systems are discussed.

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ABSTRACT

Although there is no direct connection, the incidence of Legionnaire's disease has increased concurrently with increased usage of energy efficient domestic hot water (DHW) systems, which serve as ideal growth environments for *Legionella pneumophila*, the bacteria responsible for Legionnaire's disease. The Duck Foot Heat Exchange Model (DFHXM) was developed to aid design of energy efficient thermal pasteurization systems with *Legionella* control specifically in mind. The model simulates a system design imitating the countercurrent heat exchange in the feet of ducks, an evolutionary adaption reducing environmental heat losses in cold climates. Such systems use a heat exchanger to preheat fluids prior to pasteurization and cool the same fluid after pasteurization. Thus, the design requires minimal addition of heat to achieve pasteurization temperatures and to cover environmental heat losses. This article describes the underlying principles and use of the freely available Microsoft Excel model, as well as compares results from the DFHXM to measurements of an experimental pilot system. Simulation outputs agreed well with experimental results for transient and steady-state temperatures, the largest discrepancy in steady-state temperatures being 4.6%. Lastly, we discuss the flexibility of the DFHXM to simulate a wide variety of designs with special emphasis on *Legionella* control and solar-thermal water disinfection.

1. Introduction

Use of energy efficient domestic hot water (DHW) systems has increased in recent years as energy costs and energy efficiency standards have increased. Water heating accounted for 18.7% of household energy usage for houses built in the United States between 1980 and 1989 and reduced to 17.8% for houses built between 2000 and 2009 [1]. The United States' energy efficient water heater market increased from 625,000 ENERGY STAR approved units sold in 2006 to 1 million sold in 2009 [2], and the U.S. federal minimum standards for energy factors of hot water storages tanks just increased in 2015. In 2008, the European Union set the goal of reducing the energy requirements of new buildings by 20% by 2020, and the addition of solar DHW systems has been shown as one way to reach this goal [3], and global use of solar hot water systems has been increasing. The annual global volume of solar water collectors increased from 1.8 kW_{th} per 1000 inhabitants in 2000 to 12.0 kW_{th} per 1000 inhabitants in 2012 [4], and the annual capacity of solar thermal collectors in the EU28 countries and Switzerland nearly doubled from 2004 to 2013 [5].

Cases of Legionnaire's disease, an acute form of bacterial pneumonia often caused by exposure to DHW systems with *Legionella pneumophila* infestations, have also been increasing. In the United States, the cases of Legionnaire's disease per 100,000 persons nearly tripled from 0.39 in 2000 to 1.15 in 2009 [6]. During that same time period in Europe, cases of Legionnaire's disease per 100,000 persons increased from 0.538 in 2000 to 1.10 in 2009 [7,8]. Increases in the occurrence of Legionnaire's disease cannot

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be directly connected to trends of energy efficient and renewably powered DHW use. However, *Legionella p.* grows well in water maintained between 25 and 45 °C [9] and can survive temperatures of 66 °C for several minutes [10], and these temperatures are typical in energy-efficient and solar DHW systems. As an example, energy efficient DHW systems heated by air-source or ground-source heat pumps typically have operating temperatures of 50–55 °C [11], which still permits *Legionella* growth. Although water temperatures within solar collectors can reach daily maximums of around 90 °C, storage tanks are typically maintained under 50 °C to minimize standby heat loss [12,13].

Many thermal, chemical, and irradiative methods for preventing and treating *Legionella* colonization in hot water distribution systems exist [14], the most common including hyperchlorination, super-heat-and-flush, and maintain storage tanks above 55 °C. All these methods have the downside of high cost; both thermal methods are energy-inefficient while hyperchlorination is potentially hazardous to the health of users [15].

One potentially energy and cost efficient method is to thermally disinfect water immediately prior to exiting a hot water outlet. The general system design, shown in Fig. 1, mimics countercurrent heat exchange present in the circulatory systems of many birds. Ducks, for example, have a structure of closely connected arteries and veins called *rete* in the legs and feet which act as a biological heat exchanger; warm arterial blood coming from the body donates heat to cold venal blood returning from the feet. This action reduces the energy input necessary to bring blood returning from the feet back to body temperature by a factor as large as 84 [16]. Thus, we refer to any design which transfers heat between fluid in a single continuous flow to aid a heating or cooling process a "duck foot" (DF) heat exchange system (see Fig. 1). Such systems are ideal for the point-of-use eradication of *Legionella* or other pasteurization applications such as flow through solar water pasteurization.

DF heat exchange systems are common design features in dairy pasteurization plants and flow through solar water pasteurization systems [17]. Other applications include processes during which fluids must increase in temperature before cooling. For example, the solar dairy pasteurization system presented by Quijera et al. (2011) and the solar honey pasteurizer presented by Evans and de Schiller (1997) would have improved their efficiencies by including DF heat exchange systems [18,19].

Many models exist for the design optimization of plate heat exchangers. McKillop and Dunkley (1960) first presented a thermal model for calculating fluid temperatures within the channels of plate heat exchangers using the Gill-Runge-Kutta method for solving the system of first order ordinary differential equations [20]. Gut and Pinto (2003) developed an assemblage algorithm for modeling generalized plate heat exchanger configurations which considers the temperature dependence of fluid properties within heat exchange channels and solved the system of first order ordinary differential equations using the computational software gPROMS [21]. Strelow (2000) presents a non-iterative method for modeling heat exchangers with multiple process streams and unusual geometries [22]. To the authors' knowledge, however, no models exist specifically describing DF heat exchange systems without manipulation. Additionally, existing plate heat exchanger models require knowledge of solving systems of first order differential equations and often additional, expensive computer software to run; thus, they are inaccessible to many potential users. The aim of this project was to develop a simple, easy-to-use model specific to DF heat exchange systems using widely available computer software. The model is intended to assist designers thinking of implementing DF heat exchange systems for *Legionella* spp. control or for a variety of pasteurization applications including solar water pasteurization.

2. Duck foot heat exchange model (DFHXM) description and use

2.1. Model description

A numerical Duck Foot Heat Exchange Model (DFHXM) was created in Microsoft Excel to simulate steady-state and transient fluid temperatures within a DF system. The DFHXM assumes a flat plate, single pass heat exchanger with parallel channel flow and uses simple, one-dimensional heat transfer in iterative calculations. It differs from more complicated models of plate heat exchangers by approximating multiple channels flowing in parallel as a single channel.

For a single-pass plate heat exchanger with *N* plates and *N* + 1 channels, the DFHXM uses symmetry to approximate the system as two countercurrent fluid channels, each with half the total channel volume, and scales the result by *N*. The idealizations outlined

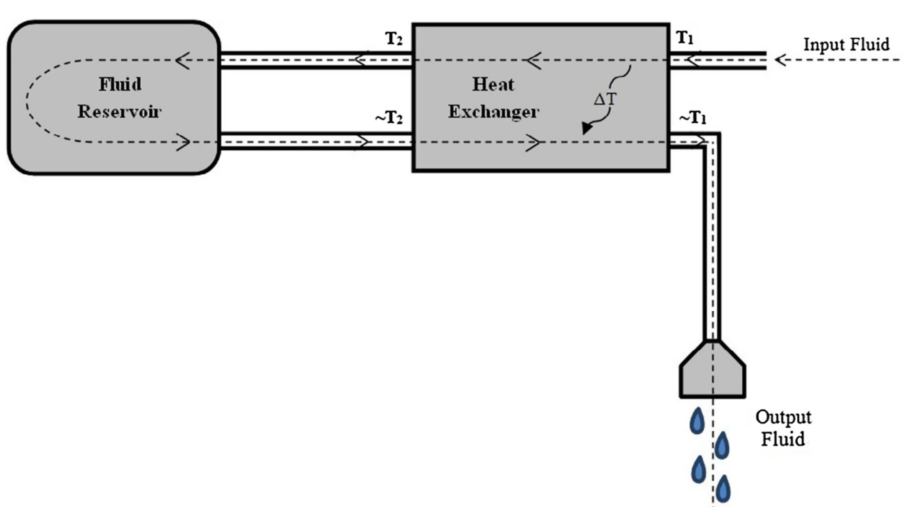

Fig. 1. General design of a "duck-foot" heat exchange system. Fluid entering at temperature T_1 changes by ΔT in the heat exchanger to T_2. After passing through some kind of reservoir, fluid re-enters the heat exchanger at a temperature very near T_2 (due to heat gains/losses to the environment). Fluid exits the heat exchanger at an output temperature near to the input temperature T_1.