Energy Policy 68 (2014) 334–339

Contents lists available at ScienceDirect

Energy Policy

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

Short Communication

Domestic hot water storage: Balancing thermal and sanitary performance

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HIGHLIGHTS

- Domestic hot water tanks are a potential demand side asset for power networks.
- A preference for bacterial growth in stratified hot water tanks has been observed.
- Temperatures in base of electric hot water tanks hospitable to *Legionella*.
- Potential exposures to unsanitary water observed.
- De-stratifying a tank to sterilise leads to reduced energy storage capability.

ARTICLE INFO

Article history:
Received 18 November 2013
Received in revised form
10 January 2014
Accepted 11 January 2014
Available online 6 February 2014

Keywords:
Thermal energy storage
Legionella
Domestic hot water

ABSTRACT

Thermal stratification within hot water tanks maximises the availability of stored energy and facilitates optimal use of both conventional and renewable energy sources. However, stratified tanks are also associated with the proliferation of pathogenic bacteria, such as *Legionella*, due to the hospitable temperatures that arise during operation. Sanitary measures, aimed at homogenising the temperature distribution throughout the tank, have been proposed; such measures reduce the effective energy storage capability that is otherwise available. Here we quantify the conflict that arises between thermodynamic performance and bacterial sterilisation within 10 real world systems. Whilst perfect stratification enhances the recovery of hot water and reduces heat losses, water samples revealed significant bacterial growth attributable to stratification ($P<0.01$). Temperature measurements indicated that users were exposed to potentially unsanitary water as a result. De-stratifying a system to sterilise bacteria led to a 19% reduction in effective hot water storage capability. Increasing the tank size to compensate for this loss would lead to an 11% increase in energy consumed through standing heat losses. Policymakers, seeking to utilise hot water tanks as demand response assets, should consider monitoring and control systems that prevent exposures to unsanitary hot water.

1. Introduction

In many parts of the world, energy is stored in sanitary hot water for the purposes of bathing, showering and cleaning. Such activities account for between 17% and 39% of household energy demand (Palmer and Cooper, 2011; van Blommestein ad Daim, 2013); a fraction that is likely to increase as building insulation standards improve (Boait et al. n.d.). Water is an excellent material for storing thermal energy because of its large heat capacity and low cost. Storing thermal energy in water is an attractive proposition given the challenges associated with alternatives such as: pumped storage, batteries and flywheels (Lindley, 2010; Moreau, 2011; Baker, 2008). In the UK, electric hot water cylinder sizes range between 74 l and 450 l (Anon, 1990), equating to 3.5 kW h to 21 kW h of energy storage. This is a potentially significant contribution to future reserve and response requirements given the increased uptake of renewable energy sources (Taylor et al., 2013) along with the increasing transition from gas fired to electrically heated systems (Wilson et al., 2013).

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http://dx.doi.org/10.1016/j.enpol.2014.01.012

Worldwide, the uptake of hot water tanks is likely to rise in line with the growth of developing economies (Hoeven, 2012; Junfeng and Runqing, 2005), this has been true in particular for solar heated tanks (Li et al., 2011); many of these systems incorporate an auxiliary electric heating element to cover periods where there is insufficient sunlight (Furbo et al., 2005).

Thermal stratification, within hot water tanks, facilitates efficient storage from multiple energy sources wherever there is a mismatch between the supply of energy and demand for hot water (Sterling and Collins, 2012; Moreau, 2011; Cole and Bellinger, 1982; Dincer and Rosen, 2002). However, whilst thermal stratification can be exploited to enhance energy storage, the temperatures that prevail within domestic systems have been associated with pathogens such as *Legionella* (Alary and Joly, 1991; Adams, 2012). *Legionella* multiplies in water at temperatures between 25 °C and 45 °C with an exponential increase in bacterial sterilisation occurring above 49 °C (Lee et al., 2008). If inhaled during activities such as showering, *Legionella* bacteria can cause a form of pneumonia called Legionnaires′ disease (Isberg et al., 2009; Schoen and Ashbolt, 2011; Brundett, 1989). In Europe, there has been an increase in such infections from 100 in 1990 to over 900 in 2007 (Anon, 2012).

This letter discusses the results of field and experimental work conducted to establish:

1. Whether bacterial growth within existing hot water systems can be attributed to thermal stratification.
2. The consequences of de-stratifying a hot water tank, to enhance sanitary performance, on energy storage capability.

1.1. *The role of thermal stratification within domestic hot water tanks*

To illustrate the role of thermal stratification, we consider energy storage within a perfectly stratified hot water tank versus a fully mixed one. The left hand side of Fig. 1 shows a simulated temperature field throughout a stratified tank during operation. Inlet water mixes in the bottom of the tank leading to a mixed zone. A thermocline separates the mixed region from a preserved zone of hot water. In practice, the heating element is positioned at least 150 mm from the bottom of the tank (Anon, 1990), this measure ensures that an initially stratified temperature distribution results after heating, leaving a cold, dense portion of water beneath the element. Segregating the heat in this manner minimises mixing from the cold inlet which is associated with reduced hot water recovery during operation (Zurigat et al., 1988).

In addition to standing heat losses, thermal performance is often evaluated by measuring the amount of exergy recovered during operation (Tiwari et al., 2009; Dincer and Rosen, 2002). The term Exergy defines the amount of useful work that is available from a unit of energy given the temperature it is dispatched at along with the ambient temperature of the environment (Cengel and Boles, 2006). In the case of a domestic hot water tank, the useful output of the system is the volume of hot water developed for the user; therefore, our analysis will emphasise an alternative parameter, referred to as the useable mass of water m_u. Before final use, hot water, stored at temperature T_o, is mixed with cold mains water at T_c, delivering useable hot water at T_u. Assuming constant density and heat capacity, the energy balance associated with the mixture of tank and mains water for a constant mass flow rate of tank water, $\dot{m}$ over time, t yields:

$$m_u(t) = \dot{m} \int_0^t 1 + \frac{T_o(t) - T_u}{T_u - T_c}\, dt \tag{1}$$

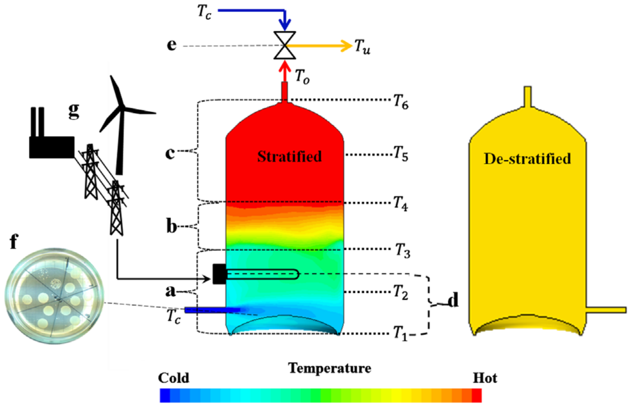

Fig. 1. (Left) Schematic illustration of temperature distribution within a 120 l stratified hot water tank. Annotated to show: (a) cold mixed zone beneath thermocline, (b) which separates mixed zone from preserved zone of energy stored as hot water, (c), (d) shows positioning of heating element to ensure stratified temperature distribution whilst (e) indicates mixing valve which delivers hot water at correct service temperature. Evidence of prolific bacterial growth is shown on plate (f) whilst (g) illustrates system as an energy storage asset within a mixed portfolio of conventional and renewable energy sources. (Right) Schematic illustration of homogenous temperature distribution throughout an equivalent tank once de-stratified.

The recovery of exergy, E_x, over time can be calculated as follows:

$$E_x(t) = \dot{m} C_p \int_0^t (T_o(t) - T_c)\left[1 + T_C / T_o(t)\right] dt \tag{2}$$

where C_p is the specific heat capacity of water.

During a draw event, we consider the standing heat losses to be negligible compared to the thermal energy drawn from the tank outlet. This allows us to treat the tank as an adiabatic system for the purposes of deriving the outlet temperature, $T_o(t)$.

In the case of a fully mixed tank, as shown on the right hand side of Fig. 1, the outlet temperature can be described by (3) during a draw off:

$$T_o(t) = T_c + [T_{init} - T_c] e^{-\frac{\dot{m}}{m_T} t} \tag{3}$$

where the outlet temperature over time varies according to the initial mass of hot water in the tank, m_T, and the initial isothermal temperature of the tank, T_{init}.

The outlet temperature from a perfectly stratified, adiabatic tank can be expressed as:

$$T_o(t) = \begin{cases} T_{init} & \text{for } 0 < t < \frac{m_T}{\dot{m}} \\ T_c & \text{for } t > \frac{m_T}{\dot{m}} \end{cases} \tag{4}$$

Processes such as plume entrainment and vertical conduction (Kleinbach et al., 1993; Fan and Furbo, 2012) mean that hot water tanks never perform according to the ideal described by Eq. (4). However, it is instructive to compare the performance of a stratified and fully mixed system by considering a draw event from an adiabatic tank. Eqs. (1), (3) and (4) provide the change in outlet temperature and useable volume yielded from the fully mixed and perfectly stratified case (Fig. 2). Here T_u is assumed to be 43 °C. In practice, T_u will vary from one application to another, in (Angel, 2012) it is recommended that temperatures do not exceed 44 °C for bathing and 41 °C for showering.

Fig. 2 indicates that 2.3 times more useable volume is recovered from the perfectly stratified tank. Considering a 120 l stratified vessel as a baseline with a height of 0.75 m, a fully mixed tank, with equivalent storage capability, would have to be enlarged with a consequent increase in surface area and standing heat loss of 70%.