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Thermal and sanitary performance of domestic hot water cylinders: Conflicting requirements

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HIGHLIGHTS

- Bacterial levels in the bottom of electrically heated tanks are excessive.
- Slow heat transfer beneath immersion element leading to inadequate temperatures.
- Field measurements confirmed by experimentally validated thermal model.
- Legionella growth model finds that immersion element position is key to sterilisation.
- Thermal stratification may break down when trying to achieve sterile conditions.

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ABSTRACT

In order to understand the sanitary implications around the demand side management of domestic hot water cylinders, microbial samples were taken from the bottom of 10 UK domestic electric hot water tanks whose heating elements are connected to a controlled off-peak supply. The results indicated high concentrations of bacteria in the water and biofilm. Microbial concentrations remained high in spite of the application of seven hours of heating during off-peak hours. Further numerical and experimental work shows that this problem arises due to the differing modes of heat transfer that prevail above and below the immersion element. The results from thermal and bacterial growth models suggest that it is impossible to achieve sanitary conditions throughout standard domestic hot water tanks without significantly increasing the heating element temperature or lowering the heating element from its current position. Raising the immersion thermostat temperature results in additional heat losses whilst lowering the immersion position compromises thermal stratification leading to uneconomical operation. Guidelines around storing hot water at temperatures that are sufficient for the purposes of sterilizing human pathogens such as Legionella, fail to take account of the conflict between thermal and sanitary performance. By better understanding the distribution of temperatures and bacteria within hot water tanks along with the associated risks, improved design and control strategies may be adopted to facilitate effective demand side management of hot water systems whilst meeting sanitary requirements.

1. Introduction

Electrically heated domestic hot water cylinders are used widely throughout Europe and America [1,2]. Operators of the UK transmission network use hot water cylinders as demand side management (DSM) assets through the control of their heating elements [Ref]. In addition to this, cylinders are becoming increasingly prevalent in buildings that are serviced by a variety of renewable energy sources such as: solar collectors, multi-fuel stoves and heat-pumps. Such systems deliver intermittent low grade thermal energy that has to be stored in order to balance the supply of heat against the demand for domestic hot water.

In addition to a user's thermal needs, hot water systems must also meet minimum sanitary requirements. UK guidelines stipulate that water should be stored at or above 60 °C and reach 50 °C at tap outlets within one minute [3]. These measures are intended to control a host of waterborne pathogens which are potentially detrimental to human health [4]. Much of the focus is on Legionella, which colonises biofilms that form on solid surfaces such as tank and pipe walls in plumbing systems [5]. If inhaled, through activities such as showering, a form of pneumonia called Legionnaires disease can result [6,7].

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Nomenclature

T_u	temperature above immersion element (°C)
t	time (s)
m_{wu}	mass of water in upper volume of tank (kg)
C_p	specific heat capacity of water (kJ kg^{-1} K^{-1})
h_i	insulation heat transfer coefficient (Wm^{-2} K^{-1})
A_s	surface area of upper portion of hot water tank (m^2)
T_a	ambient temperature (°C)
Q_e	electrical input energy (W)
m_n	nodal mass of discretised element in lower portion of tank (kg)
T_n	temperature at node n (°C)
h_w	inter-water layer heat transfer coefficient (Wm^{-2} K^{-1})
A_w	tank horizontal cross sectional area (m^2)
$A_{\Delta i}$	nodal tank cross sectional area (m^2)
P	bacterial population (Colony Forming Units)
$k(T)$	bacterial growth exponent
$\delta(T)$	bacterial sterilization exponent
R_i	Richardson's number
g	gravitational constant (ms^{-2})
β	expansion coefficient of water (m^{-3} K^{-1})
L	characteristic length scale
T_{bottom}	temperature of bottom of tank (°C)
u	water inlet velocity (ms^{-1})

In practice, it is understood that sterilizing temperatures within hot water cylinders are not always achieved due to thermal stratification [8]. The problem is particularly acute in large cylinders which has led to a configuration referred to as the thermal store in which a heat exchanger provides isolation from and heat transfer to the potable cold water supply [9]. The presence of the heat exchanger results in a loss of exergy due to the associated temperature drop. An alternative sanitation strategy involves periodic firing of an immersion element whenever renewable inputs are insufficient to ensure adequate temperatures are achieved [10,11]. This approach may lead to increased heat losses, scaling rates and the reduction in performance of renewable inputs such as heat pumps [12]. It is recommended in [13] that shunt pumps are installed on hot water systems to overcome stratification and ensure sterile conditions are attained throughout, however, it is well understood that thermal stratification is a crucial mechanism for ensuring low volumetric requirements and high thermo-economic performance within thermal energy storage systems [14,15]. It was found in [16], that retrofit of a shunt pump reduced the useable volume of hot water on a standard UK hot water cylinder by 19%.

Whilst the need to identify sanitary constraints around the dispatch of energy to hot water cylinders has been considered [17], there is little understanding of the interrelationship between thermal and sanitary performance within existing hot water systems.

To assess the prevalence of bacteria within UK hot water tanks, along with the sterilizing performance of their immersion elements, ten hot water cylinders from an apartment block were examined. The results detailed in Section 2 indicated high levels of bacteria within the lowest portion of the hot water cylinder. This is consistent with findings from a separate sample of ten apartment blocks undertaken at the same location [16], however, in this study, bacterial counts, both in the stored water and wall surface biofilm, are reported. Section 3 describes a numerical model, validated against experiment, which was used to assess the distribution of temperatures within a standard UK hot water cylinder. Section 4 describes how this model was coupled to a bacterial growth model so that a sensitivity study could be conducted to assess the influence of heating element position on required thermostat temperature. The resulting effect on system performance is considered in Section 5.

2. Apartment field study conducted to assess existing systems

A set of microbial samples were taken from a student apartment block in Oxford to assess the sterilizing performance of typical UK electric hot water cylinders in operation.

A large study in Germany, in which 452 domestic hot water systems were sampled for Legionella [18], found that where water temperatures were below 46 °C, Legionella was most prevalent. Samples were taken from the top outlet meaning that bacterial levels in the bottom of the tank were not sampled. A Danish study involving 100 apartments [19] took microbial samples using a method involving pre-installed sample ports (discussed in [20]). The sample ports were located at various positions on the hot water tank walls. The tanks involved were charged from a district heating system supply meaning the issues associated with thermal stratification arising from a single heat source within the tank (see Section 3), would not have been encountered.

An apartment block in Summertown, Oxford, UK was sampled in this study. The building comprises of 72: single, twin and 3 bedroom flats, each of which is serviced by a single hot water cylinder and 3 kW immersion element. A header tank in the loft supplies the cold inlet connections for each tank. Prior to sampling, the flats had remained unoccupied for two weeks in anticipation of renovation work and all heating elements were switched off over this duration.

Triplicate water samples were taken from a drain tap located in the bottom of the cylinder and triplicate biofilm samples were obtained using a stainless steel sampling tube with a PVC pipe running through the center opening towards a sample scoop which scraped the bottom of the tank. A syringe connected to the other end of the tube was used to capture and withdraw biofilm sections from the bottom of the tank (Figs. 1 and 2). An endoscope with camera was used to photograph the inside of the cylinder prior to sampling. Fig. 3 (left) shows an image from within one tank where heavy deposits of scale on the immersion element can be seen. The sampling process was conducted before and after the heating elements were switched on to the demand side managed circuits which fired the elements for a 7 h warm-up period. This

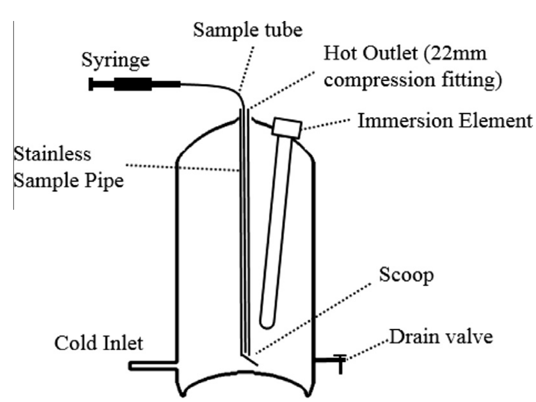

Fig. 1. Section view through hot water cylinder whilst being sampled.