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An experimental study on the influence of water stagnation and temperature change on water quality in a full-scale domestic drinking water system

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ABSTRACT

The drinking water quality changes during the transport through distribution systems. Domestic drinking water systems (DDWSs), which include the plumbing between the water meter and consumer's taps, are the most critical points in which water quality may be affected. In distribution networks, the drinking water temperature and water residence time are regarded as indicators of the drinking water quality. This paper describes an experimental research on the influence of stagnation time and temperature change on drinking water quality in a full-scale DDWS. Two sets of stagnation experiments, during winter and summer months, with various stagnation intervals (up to 168 h of stagnation) were carried out. Water and biofilms were sampled at two different taps, a kitchen and a shower tap. Results from this study indicate that temperature and water stagnation affect both chemical and microbial quality in DDWSs, whereas microbial parameters in stagnant water appear to be driven by the temperature of fresh water. Biofilm formed in the shower pipe contained more total and intact cells than the kitchen pipe biofilm. *Alphaproteobacteria* were found to dominate in the shower biofilm (78% of all *Proteobacteria*), while in the kitchen tap biofilm *Alphaproteobacteria, Betaproteobacteria* and *Gammaproteobacteria* were evenly distributed.

1. Introduction

The Dutch drinking water industry places the highest priorities in supplying adequate quantities of safe drinking water to its consumers. The so-called “Dutch secret” includes the following steps: 1) employing the best sources available; 2) applying the most efficient and state-of-the-art treatment technologies; 3) preventing re-contamination during distribution, by keeping the leakage rate low (<3%) and avoiding very low or negative pressures; 4) preventing re-growth of microorganisms, by production of biologically stable water (i.e. nutrient limited) and application of biostable materials (Van der Kooij, 2000); 5) optimization and maintenance of distribution networks (self-cleaning networks and regular flushing of networks) (Vreeburg and Boxall, 2007); 6) statuary monitoring of produced and delivered drinking water. All these approaches have resulted in a low average frequency of interruptions affecting customers (on average 7.5 min per connection per year), 99.9% of samples that are in compliance with the Dutch drinking water standards (ILT, 2015) and a high level of consumer trust and satisfaction with regards to the drinking water quality, where over 95% of the Dutch population consumes water from the tap (de Moel et al., 2006; Smeets et al., 2009). However, given the complexity of processes occurring during the water transport through distribution systems, the quality of drinking water may deteriorate, leading to hygienic (growth of pathogens and opportunistic pathogens), aesthetic (taste and odour) and operational problems (corrosion and discoloration) (Berry et al., 2006; Moerman et al., 2014; Van der Kooij, 2000; Van der Kooij and van der Wielen, 2013, Vreeburg and Boxall, 2007).

The domestic drinking water system (DDWS), being a portion of the distribution system that includes the plumbing between the

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Abbreviations

DDWS	Domestic drinking water system
AOC	Assimilable organic carbon
SIMDEUM	**SIM**ulation of water **D**emand, an **E**nd - **U**se **M**odel
SD	Standard deviation
HPC	Heterotrophic plate counts
TOC	Total organic carbon
FCM	Flow cytometry
ATP	Adenosine triphosphate
TCC	Total cell count
ICC	Intact cell count
Cu	Copper
Zn	Zinc
NOM	Natural organic matter
LNA	Low nucleic acid
HNA	High nucleic acid
KT	Kitchen tap
ST	Shower tap

water meter and consumers' taps, is the final stage in a drinking water supply system. DDWSs are characterized by long sections of small-diameter piping. For example, a study in Columbia showed that DDWSs and service pipes had ~80% of the total pipe length and ~25% of the overall surface area, and contained ~1.5% of the total volume in the whole water distribution system (Brazos et al., 1985). This high surface area to volume ratio may lead to increased chemical leaching from pipe materials, enhanced biofilm formation, and greater decay rates of the disinfectant residual (Brazos et al., 1985; Rossman et al., 1994). The Netherlands is one of the few countries where drinking water is distributed without a residual disinfectant and, as stated before, prevention of microbial growth in drinking water distribution systems is accomplished by the production of biologically stable water, with low concentrations of assimilable organic carbon (AOC<10 μg/L). However, despite the low concentrations of organic carbon that can be utilized by microorganisms, microbial growth may happen both in distribution networks and DDWSs. In addition to this, a recent study showed that opportunistic pathogens were more frequently found in the samples from DDWSs than in the samples from the distribution networks in The Netherlands (Van der Kooij and van der Wielen, 2013), which proves the importance of DDWSs in the entire process of safe drinking water supply.

The drinking water temperature is an important factor to consider when assessing water quality, as it is known to affect chemical and microbiological processes within the distribution phase (Boulay and Edwards, 2001; LeChevallier et al., 1996a; 1996b; Li and Sun, 2001; Sarver, 2010; Singh and Mavinic, 1991; Uhl and Schaule, 2004; Van der Kooij, 2003). In the Netherlands, the temperature of drinking water in distribution networks varies from a few degrees Celsius in the winter to about 20 °C in summer months (Van der Kooij and van der Wielen, 2013). Once the drinking water is delivered to a DDWS, thermal equilibrium between stagnant water and surrounding air/walls takes place. For instance, as indicated by a temperature model (Moerman et al., 2014; Zlatanovic et al., 2017) and as confirmed by measurements in the present study, the rate at which the drinking water is being warmed up to the room temperature is ~0.1 °C per minute. According to existing standards for thermal environmental conditions for human occupancies, the operative room temperatures should be 20–23.5 °C in winter and 23–26 °C in summer (ANSI-ASHRAE, 1992). If those guidelines are followed, the difference between water temperature in cold water installations and water temperature in distribution networks could even be about 20 °C during winter seasons, which may result in an increase in biological activity in DDWSs (Van der Kooij, 2003).

Long residence times which may vary from 2 to 30 days depending on the population size, is known to promote microbial growth in water distribution networks (Bartram, 2003). When it comes to DDWSs, water can further stagnate in pipes for hours, days or even weeks before being consumed. Only a limited number of studies investigated the influence of stagnation on water quality in experimental and real DDWSs (Lautenschlager et al., 2010; Lehtola et al., 2007; Lipphaus et al., 2014; Prest et al., 2013; Zhang et al., 2015). Lehtola et al. (2007) covered the impact of various stagnation intervals (40 min–16 h) on water quality in two experimental rigs, one made of copper and the other made of plastic (polyethylene) pipes. In both rigs, water stagnation (with an average temperature of fresh water of 13.9 °C) resulted in an increase in the total cell concentrations (TCC) and heterotrophic plate count bacteria (HPC). Lautenschlager et al. (2010) and Prest et al. (2013) studied the impact of overnight stagnation on microbial quality of unchlorinated water, sampled at different household taps in Dübendorf, Switzerland. Both studies found out that the overnight stagnation induces microbial growth in DDWSs, while Lautenschlager et al. (2010) also observed a change in microbial community composition after the overnight stagnation. Looking at the temperature of fresh water in the studies, Lautenschlager et al. (2010) included the information on fresh water temperature (average 9.1 °C), while Prest et al. (2013) did not report the ranges of fresh water temperatures. Lipphaus et al. (2014) and Zhang et al. (2015) also reported that water stagnation leads to increased cell concentrations and higher bacterial community metabolic activity in chlorinated water during winter months. Apart from the fact that sampling campaigns were carried out in winter months, all listed studies did not enclose information on materials of the DDWSs from which the stagnant water samples were taken. Hence, the overall conclusion that overnight stagnation results in induced microbial activity and increased microbial concentrations might not be applicable to drinking water with higher temperatures (during warmer periods) and to all plumbing materials.

Even though the water temperature and water residence time are regarded as water quality indicators in distribution networks, little is known about their joint influence on the water quality in DDWSs. To assess the impact of the stagnation time (i.e. up to 168 h of stagnation) and temperature effect on chemical and microbial quality in more detail, two sets of stagnation experiments (winter and summer) were carried out in a full-scale copper DDWS.

To study the influence of fresh water temperature on microbial activity in the stagnant water, long-term experiments with the stagnation time of 10 h (overnight stagnation) were performed over a study period of eight months. The main aim of this research was to assess the extent to which the two "surrogate" indicators for water quality (temperature and stagnation) contributes to the alteration of the drinking water quality in DDWSs.

2. Materials and methods

2.1. Description of the experimental rig

To examine the influence of stagnation time and temperature effect on water quality at tapping points in a DDWS, a full-scale DDWS was built using copper pipes (Supplemental Fig. S1).

The design of the experimental plumbing rig was done according to a plan of a two storey house (Typical Dutch House). Inside a Typical Dutch House, there are three locations where plumbing pipes go: kitchen, bathrooms/toilets, and laundry/water