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Fire sprinklers and water quality in domestic drinking water systems
A novel approach to improve public safety in homes

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INVITATION

You are kindly invited to attend the public defence of my Ph.D. dissertation entitled:

“Fire sprinklers and water quality in domestic drinking water systems”.

The defence will take place on: **Wednesday 15th of March 2017** at 12:30 in the Senaatszaal of the Aula of Delft University of Technology Mekelweg 5, Delft.

Prior to the defense, I will give a brief presentation about my research starting at 12.00.

A reception will be held directly after the defence.

Ljiljana Zlatanović

Paranymphs:
Yasmina Bennani
Mirjana Vemić

FIRE SPRINKLERS AND WATER QUALITY IN DOMESTIC DRINKING WATER SYSTEMS

Ljiljana Zlatanović

FIRE SPRINKLERS AND WATER QUALITY IN DOMESTIC DRINKING WATER SYSTEMS
Ljiljana Zlatanović

Propositions accompanying the thesis:

“Fire sprinklers and water quality in domestic drinking water systems”

By L. Zlatanović

1. In addition to the energy label, every residential property should have a fire safety label. In that way, having a residential sprinkler system would add value to the price of the property (this thesis).
2. The fire sprinkler performance does not depend merely on provided flow, but rather on the drop size and the number of drops in a drop screen (this thesis).
3. Water companies give an advice on flushing domestic drinking water systems after a period of stagnation exceeding 7 days. However, this advice seems to be based on intuitive approach rather than on scientific facts (this thesis).
4. During summer months microbiological activity appears to happen mainly in distribution networks, while during winter months most of the activity happens in domestic drinking water systems (this thesis).
5. The incorporation of sprinkler systems into domestic drinking water systems requires a holistic approach linking fire services and water companies, in which it is essential to understand and trust each other.
6. The sizing of drinking water distribution systems should be a matter of engineers and scientists (Jan Vreeburg). The philosophy “if in doubt, bigger is better” must move towards “if in doubt, do more research”.
7. The reality is unpredictable and rather complex. That is why we use models.
8. As people resist change, any new technology tends to go through a 25-year adoption cycle (Marc Andreessen).
9. 50% of cells in the human body are, in fact, microbial. Most are good, some are bad, and some are opportunistic - just like humans.
10. Doing a PhD research is similar to cooking in many ways. At the end of the day the result and a happy heart are all that matters.

These propositions are considered opposable and defendable and as such have been approved by the promotor Prof.dr.ir. J.P. van der Hoek and the copromotor dr.ir. J.H.G. Vreeburg.

Stellingen behorende bij het proefschrift:

"Fire sprinklers and water quality in domestic drinking water systems"

Door L. Zlatanović

1. Naast het energielabel moet elke woning een brandveiligheid label hebben. Op deze manier zal een woningsprinklersysteem de waarde van de woning verhogen (dit proefschrift).
2. De prestatie van een woningsprinkler is niet alleen afhankelijk van de water volumestroom, maar vooral ook van de druppel grootte en het aantal druppels in het scherm (dit proefschrift).
3. Waterbedrijven geven een advies over het doorspoelen van binneninstallaties na een periode van stagnatie langer dan 7 dagen. Dit advies lijkt echter te berusten op een intuïtieve aanpak in plaats van op wetenschappelijke feiten (dit proefschrift).
4. Tijdens de zomermaanden lijkt microbiologische activiteit vooral op te treden in het distributienet, terwijl tijdens de wintermaanden de microbiologische activiteit plaatsvindt in de binneninstallatie (dit proefschrift).
5. De opname van woningsprinklersystemen in binneninstallaties vereist een holistische aanpak van brandweer en waterbedrijven, en die kan alleen maar ontstaan als partijen elkaar begrijpen en vertrouwen.
6. Het dimensioneren en bouwen van leidingnetten wordt meer beschouwd als een vakmanschap dan als een werkgebied voor ingenieurs en wetenschappers (Jan Vreeburg). De filosofie "in geval van twijfel, groter is beter" moet veranderen in de richting van "in geval van twijfel, doe meer onderzoek".
7. De werkelijkheid is onvoorspelbaar en nogal complex. Daarom gebruiken we modellen.
8. Aangezien mensen zich verzetten tegen verandering, lijkt elke nieuwe technologie een 25-jarige acceptatie cyclus te doorlopen (Marc Andreessen).
9. 50% van de cellen in het menselijk lichaam zijn, in feite, microbieël. De meeste zijn goed, sommige zijn slecht, en sommige zijn opportunistische - net als mensen.
10. Promotieonderzoek is op vele manieren vergelijkbaar met koken. Aan het eind van de dag is het resultaat en een volaan gevoel het enige dat telt.

Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotor Prof.dr.ir. J.P. van der Hoek en de copromotor dr.ir. J.H.G. Vreeburg.

Fire sprinklers and water quality in domestic drinking water systems

A novel approach to improve public safety in homes

Fire sprinklers and water quality in domestic drinking water systems

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus Prof. Ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op woensdag 15 maart 2017 om 12.30

Door Ljiljana Zlatanović
Master of Science in Municipal Water and Infrastructure, UNESCO-IHE Institute for Water Education
geboren te Aleksinac, Servië

This dissertation has been approved by the:

Promotor	Prof. dr. Jan Peter van der Hoek
Copromotor	Dr. ir. Jan Vreeburg

Composition of the doctoral committee:

Rector Magnificus	Voorzitter
Prof. dr. J.P. van der Hoek	Delft University of Technology
Dr. ir. J.H.G. Vreeburg	Wageningen University & Research

Independent members:

Prof. dr. L.C. Rietveld	Delft University of Technology
Prof. dr. W.S.J. Uijttewaal	Delft University of Technology
Prof. dr. Z. Kapelan	University of Exeter, UK
Prof. dr. J.A.M.H. Hofman	University of Bath, UK
Prof. dr. R. Vahala	Helsinki University of Technology
Prof. dr. J.B. van Lier (reserve member)	Delft University of Technology

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Published and distributed by Ljiljana Zlatanović

To my late parents

The work presented in the thesis has been carried out at the Delft University of Technology and was supported by AgentschapNL (Project No. IMV1100047), Stichting PIT, and drinking water companies Waternet, Vitens, Oasen, PWN and Brabant Water.

SUMMARY

The effectiveness of automatic fire sprinkler systems has been proven over the decades of their application, with respect to the property damage, number of casualties and injured from fires. Nevertheless, large application of sprinkler systems in The Netherlands is not feasible due to the operational requirements of the commercially available residential sprinklers, in terms of flow and pressure, 50-80 L/min and 0.7- 1.6 bar, respectively. These requirements cannot be assured at the house level in The Netherlands. Residential fire sprinklers also suffer from a negative reputation in the drinking water world, because of the impact sprinkler system requirements would have on the design and size of distribution networks. A decade long discussion on fire flows, delivered through drinking water networks, has drawn fire fighters and drinking water companies together, exploring innovative approaches to improve public health and safety in homes. The first part of this thesis addressed the innovative design of a sprinkler head that is efficient at low flows and pressures, and could be directly incorporated in domestic drinking water systems (DDWSs). A preliminary step towards the development of a low flow and low pressure fire sprinkler included assessment of the suppression potential of a droplet screen formed by a sprinkler under low flow and low pressure conditions. The investigation included building a model of the atomization process and incorporating the drop-combustion sub model. Novel parameters Theoretical Heat Capacity (THC), Evaporate Heat Capacity (EHC) and Specific Heat Capacity (SHC), were introduced. Based on those parameters it was concluded that sprinkler performance is not directly proportional to the supplied flow and pressure, but depends on the drop size and the number of the drops in a screen.

Following these findings, an experimental study on spray characteristics was conducted, applying different sprinkler configurations and various operational flow and pressure ranges. The experimental results showed that initial spray characteristics are greatly influenced by the geometry of the sprinkler head. The results from the experimental investigation also revealed that it is possible to obtain outstanding sprinkler efficiency under low flow and pressure ranges, as the sprinkler operating with a flow of 17 L/min might still deliver around 90% of the specific heat capacity of the sprinkler operating with a flow of 49.5 L/min.

Once the first goal of the research was accomplished, a second step was taken to explore the influence of plumbing extension for sprinkler system accommodation on water quality, because adding a sprinkler system to the DDWS must not jeopardize the quality of the drinking water. Two DDWSs (conventional and extended) models were built in EPANET to simulate two surrogate parameters for water quality, namely water residence time and temperature. The models were run according to the stochastic SIMDEUM demand patterns. The model outcomes showed that temperature and residence times in DDWSs are mainly influenced by the water consumption patterns and are limitedly dependent on the size and layout of the DDWSs. The temperature model showed that, if left to stagnate, water quickly warms up, as only in 4 hours, and the stagnant water temperature becomes the same as the ambient temperature in winter months. Moreover, the model showed that drinking water is being warmed up by 0.5 to 2°C within the copper DDWSs, namely from the inlet point to the tap in use, depending on how far from the inlet point the demand takes place.

Given the importance of temperature and stagnation on microbiological and chemical parameters, an experimental study was conducted in order to: 1) validate the temperature model; 2) study the influence of the stagnation time on drinking water quality parameters; 3) determine to what extent the extension of the plumbing has an impact on drinking water.

Two full-scale DDWSs, one resembling a conventional system (C-S) and the other extended with the piping for incorporation of a residential sprinkler system (E-S), were built and run according to one year stochastic demand with time steps of 10 seconds. The drinking water temperature was measured at each point-of-use in the systems and the data set was used for temperature model validation. Temperature model validation was done by employing a combination of graphical and statistical techniques. Based on the statistical analysis, it was concluded that the model is able to reproduce the temperature profiles within a copper DDWSs.

To study the effects of stagnation on drinking water quality, two sets of stagnation experiments, winter and summer, with different stagnation intervals (up to 168 hours of stagnation) were carried out in the C-S. Drinking water was sampled at two different taps, a kitchen tap and a shower tap. Stagnation of water in DDWS lead to increased concentrations of both copper and the zinc in water, while the total organic carbon (TOC) content was found to decrease with stagnation time, during both winter and summer experiments.

Microbial properties of stagnant water were found to be different under winter and summer conditions. During the winter experiments, intact cell concentrations (ICC) increased on average 2-fold in all water samples after the stagnation of more than 10 hours. This increase was also measured in heterotrophic plate counts (2–200-fold) and adenosinetriphosphate (ATP) concentrations (4-8-fold). During the summer experiments, on the contrary, a 2-5-fold reduction in ICC was observed after stagnation for more than 4 hours.

Overnight stagnation of 10 hours was found to influence the microbial characteristics of water, whereas the temperature of fresh water played the critical role for the growth pattern; up to 1.5-fold increase in ICC and up to 7-fold increase in ATP levels were measured in stagnant samples if the fresh water temperature was lower than 17°C, while up to 2-fold reduction in ICC and up to 5-fold in ATP concentrations were found if the temperature of fresh water was higher than 17°C.

More biofilm was formed in the shower pipe than in the kitchen pipe, quantified by total and intact cell count. Even though *Protobacteria* were the most abundant bacteria in both biofilm samples, *Alphaproteobacteria* were found to dominate in shower biofilm (78% of all *Proteobacteria*), while in the kitchen tap biofilm *Alphaproteobacteria, Betaproteobacteria* and *Gammaproteobacteria* were evenly distributed. These findings suggest that different biofilms composition may exist within one DDWS, which can be attributed to the influence of microclimate and variation of consumption patterns at different taps on biofilm formation.

In addition to this, to study the influence of the added plumbing on the quality of both fresh and 10 hours stagnant water in two full scale DDWSs, stagnation experiments were performed twice a month during a study period of 8 months. Leaching of copper and zinc from the copper pipes and brass fixtures was observed in all stagnant water samples: 30-50 fold copper increase and 3-7 fold zinc increase. TOC content decreased with 5-15% during the overnight stagnation in both systems. Microbial activity, measured by flow cytometry (FCM), ATP concentrations and heterotrophic plate count (HPC), depended on the temperature of fresh water samples which varied from 6°C to 23.5°C. The temperature of stagnant water in DDWSs was equal to the ambient temperature and was in the range of 16°C to 26°C. Enhanced microbial activity was observed in both systems when the fresh water temperature was lower than an observed tipping point (15°C for the HPC and 17°C for the FCM and ATP measurements, respectively).

Characterization of microbial populations in water samples and harvested biofilms showed that among the identified sequences of phylum bacteria, *Protobacteria* were the most dominant species. High similarity between water and biofilm communities, >98% and >70-94% respectively, indicated that the extension of the DWWSs did not significantly affect neither the microbial quality of fresh drinking water, nor the biofilm composition, during 14 months of experimental investigation. Though some differences were observed between the stagnant water samples from the shower taps in the C-S and E-S, insignificant differences between all fresh water samples were found for all examined parameters, meaning that the tap flushing can restore the quality of the drinking water quality in DDWSs in both systems.

SAMENVATTING

De effectiviteit van automatische woning sprinklersystemen ten aanzien van de schade aan eigendommen, het aantal slachtoffers en gewonden bij branduitbraak is bewezen in jarenlange toepassing. De brede toepassing van sprinklerinstallaties is echter nog niet haalbaar vanwege de operationele eisen van de commerciële woningsprinklers, qua volumestroom en druk: 50-80 L/min en 0.7-1.6 bar. Aan deze eisen kan niet worden voldaan op “huis niveau” in Nederland. Woningsprinklers hebben daarnaast ook last van een negatieve reputatie in de drinkwaterwereld, vanwege de impact die commercieel verkrijgbare sprinklersystemen zouden hebben op de eisen van het ontwerp van het leidingnetwerk. Een tien jaar lange discussie over het bluswatervolume en de impact daarvan op het ontwerp van het leidingnetwerk, hebben brandweer en drinkwater bedrijven samengebracht om innovatieve benaderingen te verkennen ter verbetering van de volksgezondheid en veiligheid in huizen.

Het eerste deel van het proefschrift is gericht op een innovatief ontwerp van een sprinkler kop die efficiënt werkt bij lage volumestromen en druk en die direct kan worden aangesloten op de binneninstallatie. De eerste stap op weg naar de ontwikkeling van een lage volumestroom- en lage druk sprinkler bestond uit een evaluatie van het suppressie potentieel van een druppel scherm die door een sprinkler onder lage volumestroom en lage druk gevormd wordt. Het onderzoek omvatte het bouwen van een mathematisch model van het vernevelingsproces en de integratie van het druppel-verbranding sub-model. Nieuwe parameters zoals de theoretische hitte capaciteit (THC), de effectieve hitte capaciteit (EHC) en de specifieke hitte capaciteit (SHC) zijn ontwikkeld. Op basis van deze parameters werd geconcludeerd dat de sprinklerprestatie niet recht evenredig zijn met de geleverde volumestroom en druk, maar meer afhankelijk zijn van de grootte van de druppels en het aantal druppels in een scherm.

Naar aanleiding van deze bevindingen werd een experimentele studie gedaan naar sproei kenmerken met verschillende sprinkler configuraties en onder verschillende operationele volumestromen en een verschillende drukken. De experimentele resultaten toonden aan dat de sproei kenmerken sterk beïnvloed worden door de geometrie van de sprinkler kop. Uit de resultaten van het experimentele onderzoek bleek ook dat het mogelijk is om een uitstekende sprinkler efficiëntie onder lage volumestroom en lage druk te bereiken, aangezien een woningsprinkler (met een volumestroom van 17 L/min) nog steeds ongeveer 90% van de specifieke hittecapaciteit van de commerciële sprinkler (met een volumestroom van 49.5 L/min) kan leveren.

Nadat het eerste doel van het onderzoek was bereikt, betrof de tweede stap de studie naar de invloed van de uitbreiding van een binneninstallatie met een sprinklerinstallatie op de kwaliteit van het water, aangezien een toegevoegd sprinkler systeem de kwaliteit van het drinkwater niet in gevaar mag brengen. Twee modellen van een binneninstallatie (standaard en uitgebreid met een sprinklerinstallatie) werden in EPANET gebouwd om twee surrogaat-parameters voor de kwaliteit van het water te simuleren, namelijk de verblijftijd van het water en de temperatuur. De stochastische SIMDEUM patronen zijn gebruikt om het verbruik te modelleren. Uit de resultaten van de modellen bleek dat de temperatuur en verblijftijd in binneninstallaties vooral worden beïnvloed door de consumptiepatronen van water en slechts beperkt afhankelijk zijn van de grootte en de indeling van de binneninstallaties. Uit het temperatuurmodel bleek ook dat stilstaand water snel opwarmt, aangezien binnen 4 uur de temperatuur van stilstaand water gelijk wordt aan de kamertemperatuur gedurende de winter maanden. Bovendien bleek dat in die periode drinkwater in alle gevallen wordt opgewarmd met 0.5 tot 2°C in de koperen binneninstallatie, namelijk vanaf het inlaatpunt tot de gebruikte kraan, afhankelijk van hoe ver van het inlaatpunt deze zich bevindt.

Gezien het belang van de temperatuur en stagnatie op microbiologische en chemische parameters werd een experimenteel onderzoek uitgevoerd om: 1) het temperatuurmodel te valideren; 2) de effecten van de verblijftijd op drinkwater-kwaliteitsparameters te bestuderen; 3) te bepalen in welke mate de uitbreiding van de binneninstallatie gevolgen heeft voor de drinkwaterkwaliteit.

Twee experimentele binneninstallaties, één conform een standaard systeem en de andere uitgebreid met leidingen voor een woningsprinkler installatie, werden gebouwd en gedurende een jaar gevoed met drinkwater op basis van stochastische SIMDEUM consumptiepatronen met tijd stappen van 10 seconden. De temperatuur van het drinkwater werd op elk punt van gebruik in de systemen gemeten en de gegevens werden gebruikt voor het valideren van het temperatuur model. Validatie van het temperatuurmodel werd gedaan door een combinatie van grafische en statistische technieken. Op basis van de statistische analyse werd geconcludeerd dat het model de temperatuurprofielen binnen een koperen binneninstallatie kan reproduceren.

Om de effecten van stagnatie van drinkwater op de kwaliteit ervan te bestuderen, werden twee sets van stagnatie experimenten uitgevoerd, winter en zomer, met verschillende stagnatie intervallen (tot maximaal 168 uur stagnatie). Water werd bemonsterd bij twee verschillende kranen, een keuken kraan en een douche kraan. Stagnatie van het water leidde tot verhoogde koper- en zink concentraties in het stilstaande water, terwijl de totale hoeveelheid organische koolstof bleek te verminderen met de stagnatie tijd, in zowel het winter als het zomer experiment.

Microbiële karakteristieken van het stilstaande water bleken verschillend te zijn in de winter en zomer. Gedurende de winter experimenten, stegen intacte cel concentraties (ICC) gemiddeld met een factor twee in alle watermonsters na stagnatie langer dan 10 uur. Deze stijging werd ook gemeten in de kiemgetallen (2-200-voudig) en adenosinetrifosfaat (ATP) concentraties (4-8voudig). Tijdens de zomer-experimenten werd echter een 2-5-voudige daling van ICC waargenomen na stagnatie van meer dan 4 uur.

Stagnatie gedurende 10 uur in de nacht bleek de microbiële activiteit in het water te beïnvloeden, terwijl de temperatuur van vers water de kritische rol speelde voor het groeipatroon; een maximaal 1.5-voudige *toename* van ICC en een maximaal 7-voudige toename in ATP concentraties werden gemeten in stilstaande monsters als de verswater temperatuur lager dan 17° C was, terwijl een maximaal 2-voudige afname van ICC en een maximaal 5-voudige afname in ATP concentraties werden gevonden, als de temperatuur van het verse water hoger dan 17 ° C was.

Er ontstond meer biofilm in de douche leiding dan in de keuken leiding, gekwantificeerd door het totale aantal getelde cellen en de getelde levende cellen. Hoewel

Protobacteria de meest voorkomende bacteriën in beide monsters van de biofilm waren, bleken *Alphaproteobacteria* te domineren in de biofilm van de douche leiding (78% van alle *Proteobacteria*), terwijl in de biofilm van de keuken leiding *Alphaproteobacteria*, *Betaproteobacteria* en *Gammaproteobacteria* gelijkmatig verdeeld werden gevonden. Deze bevindingen wijzen erop dat er verschillende biofilm samenstellingen kunnen bestaan in een binneninstallatie, wat kan worden toegeschreven aan de invloed van microklimaat en variatie van consumptiepatronen bij verschillende kranen op de biofilm vorming.

Daarnaast werd een 8 maanden lang studie uitgevoerd naar de invloed van de uitbreiding van de binneninstallatie op de kwaliteit van vers en 10 uur stilstaand water in de twee experimentele binnenistallaties, en twee maandelijks werden overnacht stagnatie-experimenten uitgevoerd. Afgifte van koper en zink van de koperen leidingen en messing koppelingen werd waargenomen in alle stilstaande watermonsters: een 30-50 voudige toename voor koper en een 3-7 voudige toename voor zink. De totale organische koolstof (TOC) concentratie daalde met 5-15% gedurende de nachtelijke stagnatie in beide systemen. Microbiële activiteit, gemeten door "flow cytometry" (FCM), ATP concentraties en kiemgetal tellingen (HPC), was afhankelijk van de temperatuur van de vers water monsters (de temperatuur van vers water varieerde van 6°C tot 23,5°C). De temperatuur van het stilstaande water in de binneninstallaties was gelijk aan de omgevingstemperatuur en varieerde van 16°C tot 26°C. Verhoogde microbiële activiteit werd waargenomen in beide systemen bij een vers water temperatuur lager dan een omslagpunt (15°C voor de HPC en 17 °C voor de FCM en ATP metingen). Uit de karakterisering van bacteriële gemeenschappen in watermonsters en biofilms bleek dat onder de geïdentificeerde sequenties van phylum bacteriën, Protobacteria de meest dominante soort was. Grote gelijkenis tussen water en biofilm gemeenschappen, > 98% en > 70-94% respectievelijk, geeft aan dat de uitbreiding van de binneninstallaties geen significant effect heeft op de microbiologische kwaliteit van vers drinkwater en biofilm samenstelling, gedurende 14 maanden van experimenteel onderzoek. Hoewel er enkele verschillen werden waargenomen tussen de monsters van stilstaand water van de douche kranen in het standaard systeem en het uitgebreide systeem, werden alleen niet-significante verschillen tussen alle verse water monsters voor alle onderzochte parameters gevonden. Dit betekent dat het doorspoelen van de kraan de kwaliteit van het drinkwater in binneninstallaties in beide systemen kan herstellen.

CONTENT

CHAPTER 1

1 INTRODUCTION

1.1 DRINKING WATER SUPPLY AND FIRE FIGHTING

The major function of drinking water distribution networks is to supply sufficient drinking water quantities to the consumers, at adequate pressure ranges and with acceptable quality. Apart from the actual drinking water demand, the majority of the drinking water distribution networks supply fire flows, which are the amounts of water needed to extinguish fires by firefighting services. The usual demand of a fire hydrant (30 to 60 m^3/h) is delivered through the network with pipes of at least 100 mm, while the maximum allowable spacing between the hydrants and objects is 40 m in The Netherlands (NVBR 2003). These spatial and flow requirements have resulted in the phenomena of generously sized drinking water distribution networks. Low drinking water velocities and prolonged residence times are usually associated with the generously sized networks, which in turn, may promote sediment accumulation and affect water quality issues like discoloration, low disinfectant residual and microbiological regrowth (Vreeburg and Boxall 2007).

In spite of the fire flows, delivered through generously sized drinking water distribution networks, and despite the efforts put to improve the fire safety in homes in the last decade (e.g. public education campaigns on the application of smoke detectors, introduction of reduced ignition propensity (RIP) cigarettes, initiative of firefighting service to restrict the sale of the furniture that doesn't meet flame retardant standards), the number of residential fires and fire fatalities remains stable in The Netherlands. Around 7,000 dwelling fires occur each year, leaving on average 45 casualties (Figure 1-1) and dozens more injured.

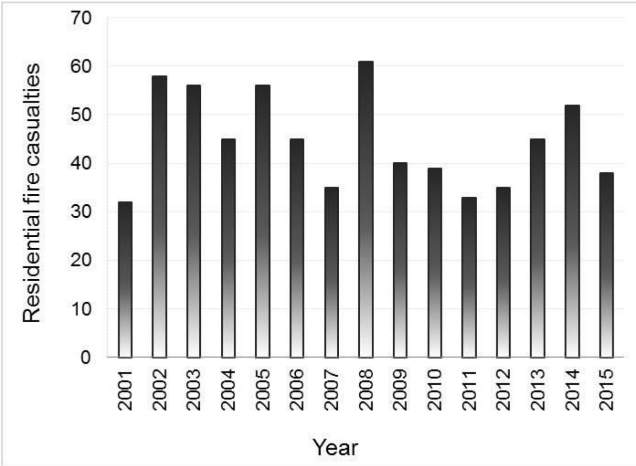

Figure 1-1 The number of residential fire casualties over the past 15 years (2001-2015), excluding the firefighting personnel casualties (NIFV 2001 - 2015a)

The discussion about the fire flows supplied by generously sized water distribution networks and their effectiveness with regard to the fire fatalities, has put the fire fighters and drinking water companies on the same side, jointly seeking to identify and evaluate novel approaches to improve public health and safety: approaches that on the one hand improve the residential fire safety, and on the other hand avoid the use of generously sized drinking water distribution networks. One of the discussed approaches was an application of automatic sprinkler systems on a large scale.

An automatic fire sprinkler system is one of the active fire repression measures which prolongs the evacuation time of residents and contains the fire before the water from fire hydrants can be used by firefighting personnel. Statistics show that automatic fire sprinklers have helped to prevent more than 80% of residential fire casualties and around 70% of property damage (Hall et al. 2012). The technical problem of widespread implementation of domestic fire sprinkler systems in The Netherlands is the required water flow and pressure for a conventional fire sprinkler head, which is in the order of 50 to 80 L/min and 0.7 to 1.6 bars, respectively. The required flow for the conventional sprinkler system, as such, could never be supplied by a standard drinking water connection in The Netherlands, because the available flow and pressure typically found at more distant locations in typical Dutch homes are 20 L/min and 0.5 bar, respectively. To overcome this obstacle, a breakthrough in the design of the sprinkler head is required. This breakthrough should make it possible to effectively use the flow and pressure thresholds which are available in typical Dutch homes, in order to provide extra escape time to the residents. If the innovation in the sprinkler head is successfully delivered, another technical aspect that should be further considered is the application of the domestic sprinkler systems, because these systems could be installed in three ways: as separated, combined and fully integrated systems in DDWSs (see Figure 2-5).

Separated domestic fire sprinkler systems, as the name implies, are separated from DDWSs and the connection between the DDWS and fire sprinkler system is equipped with a non – return valve. The major drawbacks of this approach would be regular testing of the valve, which increases the maintenance costs, and accidental shutdown of the valve. Combined systems are to a certain extent separated, but would deliver a flow through the sprinkler installations for a non-potable use, such as flushing a toilet. In this approach, each time the toilet is flushed, the functionality of the separated system is tested. Integrated systems are fully incorporated into the DDWSs, which represents one of the most promising approaches in terms of the functionality and maintenance costs. Still, a complete sprinkler system integration into a conventional DDWS would change the layout of DDWSs, as additional sprinkler loops with larger diameters would be required, which may have an impact on the quality of drinking water at the consumers' tap.

In DWDSs, the drinking water residence time and temperature may be considered as surrogate parameters for water quality. Residence time in distribution networks is a function of several parameters, such as: the distance from the water treatment facility, pipe diameters (which vary from 20 mm for service pipes to 1600 mm for the transmission mains), water velocities which are driven by the drinking water consumption and population size (Bartram 2003). Residence times, which may vary from 2 to 30 days are known to promote microbial re-growth in drinking water distribution networks (Kerneïs et al. 1995, Nescerecka et al. 2014, Prest 2015, Uhl and Schaule 2004). In the DDWSs, on the other hand, water may stagnate in pipes for hours, days or even weeks before the consumption takes place. Recent studies showed that overnight stagnation of water in DDWSs promotes overall microbial activity and richness (Lautenschlager et al. 2010, Prest 2015). Moreover, stagnation of water in DDWSs leads to leaching of various compounds from pipes and fixtures, such as copper, zinc and organic compounds (Lehtola et al. 2007, Sarver et al. 2009, Zhang et al. 2014).

Drinking water temperatures vary over the year due to the seasonal raw water temperature fluctuation and due to seasonal variation of the ambient temperature. Typical drinking water temperatures in distribution systems range from several degrees in winter to 25°C in summer in The Netherlands (Blokker and Pieterse-Quirijns 2013, Prest 2015). The importance of drinking water temperature lays in its effect on the chemical and microbiological processes within the water distribution (Boulay and Edwards 2001, Kerneïs et al. 1995, LeChevallier et al. 1996a, LeChevallier et al. 1996c, Li and Sun 2001, Liu et al. 2013, Prest 2015, Sarver 2010, Singh and Mavinic 1991, Uhl and Schaule 2004, Van der Kooij 2003). In the DDWSs, where water stagnates most of the time, drinking water quickly warms up to the room temperature. According to 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). These guidelines imply that the difference between water temperature in cold water installations and water temperature in distribution networks could even be about 20°C during the winter season, which may result in increase in biological activity in DDWSs (Van der Kooij, 2003).

1.2 RESEARCH GOAL AND OBJECTIVES

Despite the advances regarding the fire safety measures at the home level, and in spite of the fire flows supplied by large water distribution networks, the number of fire casualties stayed constant over the last decade in The Netherlands. The main goal of this thesis was to develop and evaluate a novel approach of an additional residential fire safety measure, by means of a full integration of the residential sprinkler system into DDWSs.

The specific research objectives were as follows.

1. To develop design criteria for a fire sprinkler system that operates under low flow and low pressure thresholds typically found in Dutch houses.
2. To develop and validate a model which predicts the water temperature dynamics in DDWSs.
3. To evaluate the importance of the two water quality surrogate parameters, temperature and stagnation time, with regard to the quality of the drinking water
4. To study the influence of the added plumbing for the sprinkler integration on the water quality and biofilm in DDWSs.

1.3 THESIS OUTLINE

Research question	Outline
What is the current linkage between drinking water supply and fire safety? What are the possibilities to improve public safety at the residential level?	**Chapter 2** is a literature review which shows the linkage that exists between drinking water supply, fire and public safety at the residential level in The Netherlands. Based on the review, a novel concept of the automatic domestic fire sprinkler system is proposed as the most efficient technology that, if applied on a large scale, may minimize the impact of residential fires.
What are the key design parameters that influence spray characteristics under low flow and low pressure conditions? Is it possible to obtain sufficient spray characteristics, in terms of heat capacity, under low flow and low pressure conditions?	**Chapter 3** investigates the initial spray characteristics affected by sprinkler design parameters. Specific attention was given to the low pressure ranges and low flows, 0.5 bar and 20 L/min, respectively, which correspond to operational thresholds in the Dutch DDWSs.
How to model water temperature dynamics in DDWSs? What are the most sensitive parameters when modelling water temperature at the household level?	**Chapter 4** describes a method to model a surrogate parameter for water quality, temperature, in DDWSs. The evaluation of the model performance was accomplished by comparing the modelled results with experimental measurements of flow and temperature obtained from two full scale DDWSs.

Research question	Outline
What is the influence of water stagnation on water quality in DDWSs? Is stagnant water of the same quality during winter and summer months?	**Chapter 5** describes the influence of water stagnation, on the drinking water quality in DDWSs. To study this influence of water stagnation on drinking water quality a full scale DDWS was operated for 14 months according to the water demand patterns generated by SIMDEUM.
What happens to the quality of fresh and stagnant water if a conventional DDWS is modified/extended with plumbing for accommodation of fire sprinklers?	**Chapter 6** shows the impact of added plumbing to DDWSs on the water quality. The investigation was performed by using two full scale DDWSs (one resembling the conventional DDWS, and the other with extra pipe loops for the sprinkler accommodation) that were simultaneously run according the identical water demand patterns.

Chapter 7 summarizes the overall conclusions and recommendations of the thesis.

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CHAPTER 2

2 FIRE, DRINKING WATER AND SAFETY

Abstract

In The Netherlands, the majority of fire fatalities happen in the residential buildings and numbers of the casualties remain stable throughout years, despite all kinds of improvements in the residential fire safety area. Residential fire safety can be greatly improved by large scale application of residential sprinklers. However, conventional fire sprinklers require higher flows and pressure than those delivered at the standard connection in The Netherlands. In this chapter, a review on the linkage between fire, drinking water and safety is given, including a novel approach towards providing extra fire safety, by use of what we all have in homes – drinking water.

Keywords: fire, fire sprinklers, drinking water, DDWS

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2.1 FIRE FIGURES AND FACTS

Worldwide, 300,000 casualties per year are reported due to the fire burns (WHO 2011a), while the majority of fire fatalities are related to inhalation of toxic gases produced during combustion (Gann et al. 1994). In EU countries, 2.0 – 2.5 million fire accidents are reported each year, leaving on 20,000 – 25,000 fire fatalities and 250,000 – 500,000 fire injuries per year (NIFV 2009).

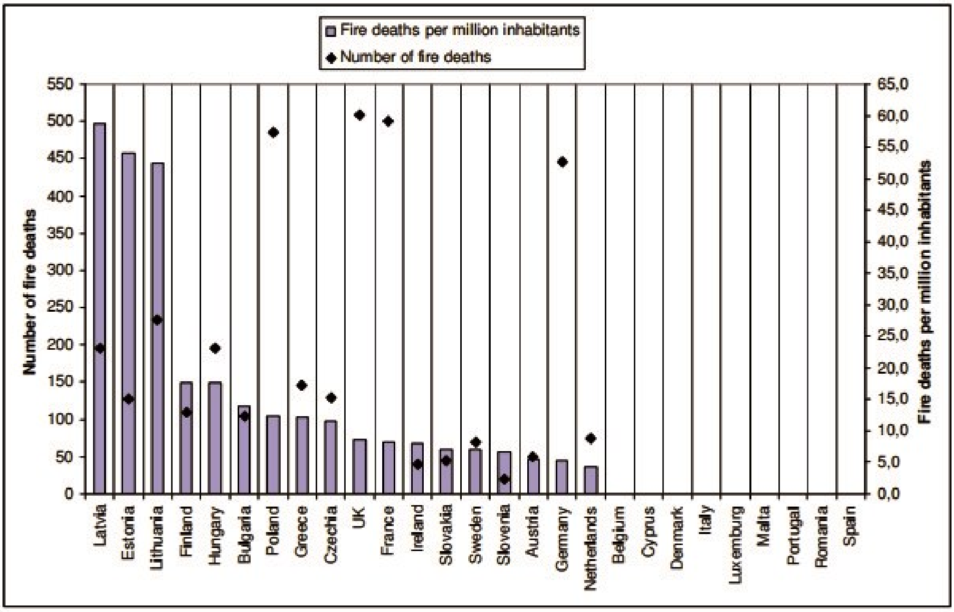

Figure 2-1 Number of fire deaths worldwide (NIFV 2009)

The majority of the fires occur in residential environments (Figure 2-2) while most of the fire casualties are found at night, when residents are asleep (Gann et al. 1994, Irvine et al. 2000). Statistics further show that the fatal incidents are more frequently caused by human behaviour, rather than technical failures of the domestic appliances, whereas smoking is listed as one of the leading causes for residential fires, accounting for nearly 50% of all dwelling fires (Holborn et al. 2003).

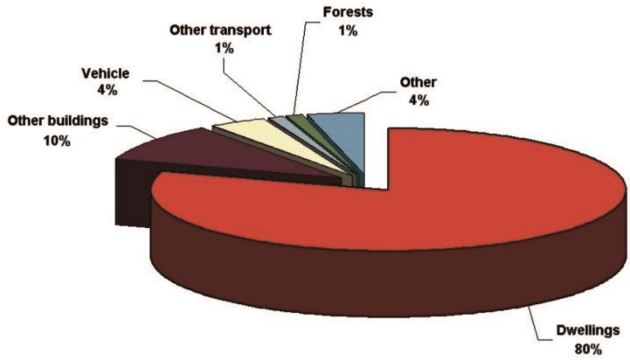

Figure 2-2 Distribution of fire deaths by fire origin (Brushlinsky et al. 2006)

In the Netherlands, particularly, around 7,000 dwelling fires occur each year, resulting in 45 fatalities on average and dozens more injured (NIFV 2001 - 2015). By looking closely at the population age structure of fire victims over the past 15 years, it was found that around half of fire victims are 60 years old or older, which was most likely due to the limited mobility of this age group. Since the aging of Dutch population is considered to continue in the coming decennia and is expected to reach its peak around 2040 (when nearly a quarter of the Dutch population will be over 65 years old) (Nimwegen 2012), a reasonable expectation is that the number of the older fire victims will increase in future.

One of the crucial reasons why the number of fatalities does not decline over the years (see Chapter 1 – Figure 1-1), is that the time required to escape a residential fire has decreased from 17 to 3 minutes (Bukowski et al. 2007, Bukowski et al. 1975). At the time when the escape time was estimated to be 17 minutes, houses and their interiors were decorated with natural materials (wooden furniture, wool carpets, cotton textiles, etc.). This trend has changed with the era of synthetic materials, and today most of the residential occupancies contain synthetic materials that can ignite readily and lead to the fast fire spreading and release of toxic gases. Therefore, critical conditions are reached in only 3 minutes, while the response time of fire service is around 8 minutes (Gadet 2009).

Over the past decades, significant efforts have been made to improve and protect the safety and health of the public and firefighting personnel. One of the basic fire safety improvements was a historic decision by drinking water companies to supply fire flow through hydrants. The decision to have fire flows incorporated in the water distribution systems, probably has its roots in times when the water mains were made from wood. In those times, once a fire occurred, the fire fighters would drill a hole in a wooden main, in order to collect water to fight the fire. As soon as the fire was extinguished, a fire plug would be used to seal the wooden main. Not very long after the fire plugs, with accelerated use of cast iron, the early form of fire hydrants in forms of stand pipes evolved (Walski 2006).

Other fire safety improvements in homes included public educational campaigns on smoke detectors which have yielded ~70% coverage of smoke detectors in the Netherlands (Kobes et al. 2016), use of fire retardant paper in all cigarettes (self-extinguishing cigarettes) introduced in November 2011 (NIFV 2013) and an initiative of firefighting service to restrict the sale of furniture that doesn't meet flame retardant standards. Moreover, the discussion over the fire flows supplied by drinking water companies through the large distribution networks has set fire fighters and drinking water companies together in the hunt for new approaches to improve public health and safety. One of the discussed approaches is application of residential fire sprinkler systems on a large scale.

2.2 RESIDENTIAL FIRE SPRINKLER SYSTEM

Residential fire sprinkler system, Figure 2-3, is an activate fire protection measure which doesn't solely extend the evacuation time of residents, but also contains the fire before the firefighters reach the event of fire.

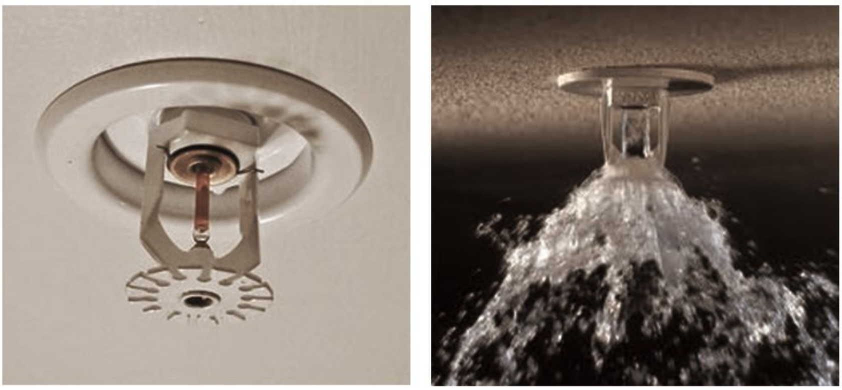

Figure 2-3 Photos of residential automatic fire sprinklers. Left photo: not activated sprinkler (source: http://www.cyfs.ca/en/fireprevention/residential_sprinklers.asp), right photo: activated sprinkler (source: http://chattanoogafire.com/?page_id=93)

A fire sprinkler head itself, is a device that automatically activates, when heated to a predetermined point, in the case of a fire. Statistics show that fire sprinklers have proven to prevent more than 80% of residential fire casualties and around 70% of property damage (Hall et al. 2012). Despite the fact that first sprinkler patent dates from 1874 (Ford 1997), application of sprinklers in Europe is mostly limited to industrial usage, due to emotional and technical barriers (Center 1995). The emotional barriers are associated with “Smoke detector” and “Hollywood” syndromes. The smoke-detector syndrome comes from a negative impression about the smoke detectors, which is a result of their activations for no obvious fire reason. Smoke from a cigarette or cooking is able to activate a smoke detector, but will never activate a sprinkler head. The sprinkler head goes off only if a certain temperature is reached at the ceiling, around the sprinkler head itself. The Hollywood syndrome is a consequence of scenes from movies, whereas if one sprinkler goes off, they all go off. This is not true, because only the sprinklers close to the fire flame will be heated to a predetermined point and go off subsequently.

The technical barrier has been, nevertheless, more challenging. Commercially available sprinkler heads are efficient under flows and pressures, which is in the order of 50 to 80 L/min and 0.7 to 1.6 bar, respectively. This can never be supplied by a standard drinking water house connection in the Netherlands, where water flow and pressure at a household level are considerably lower, approximately 30 l/min and 0.5 bar, respectively, at the most distant location in a household. Installation of a sprinkler system including the commercially available sprinklers heads would require a separate infrastructure: a reservoir and a pump. Such a system should be maintained and tested regularly, which would make it expensive and non-applicable on a large scale.

In order to promote sprinkler implementation on a large scale, a novel concept of a residential fire sprinkler system is needed. The first step in developing the concept should include a design of an innovative sprinkler head that is efficient under low flow and low pressure thresholds, while the second step should engage possible installation approaches of the sprinkler systems with no or negligible influence on water quality in a domestic drinking water system.

2.3 TYPICAL DUTCH HOUSE AND SPRINKLER INSTALLATION

Most of the dwellings in the Netherlands are terraced houses which accounts for 62% of the total, while 11% are detached - single family houses and 27% are apartments (as cited in Majcen et al. 2013). A terraced house (Typical Dutch house) is usually two to three floors high, adjoined by at least two more identical houses. The Typical Dutch house has two to three bedrooms, kitchen, living room, toilet, bathroom and attic - if the house is 3 floors(see Figure 2-4).

Figure 2-4 Typical Dutch house (terraced house) plan (left photo source: http://www.bamwoningbouw.nl/nl-nl/1/85/doorgroei.aspx; right photo source: http://nieuwbouw.bouwfonds.nl)

Inside the Typical Dutch house, there are three locations where plumbing pipes go; kitchen, bathrooms/toilets, and laundry/water heater room. On the first floor of the house the kitchen (with a hot-cold taps and a dishwasher) and a guest toilet (with a toilet bowl and a washbasin) are located. On the second floor the family bathroom (with a toilet bowl, shower and a sink) is placed, while at the third floor a washing machine and a hot water boiler are present.

Three possible approaches of a sprinkler system installation in a Typical Dutch house are presented in Figure 2-5.

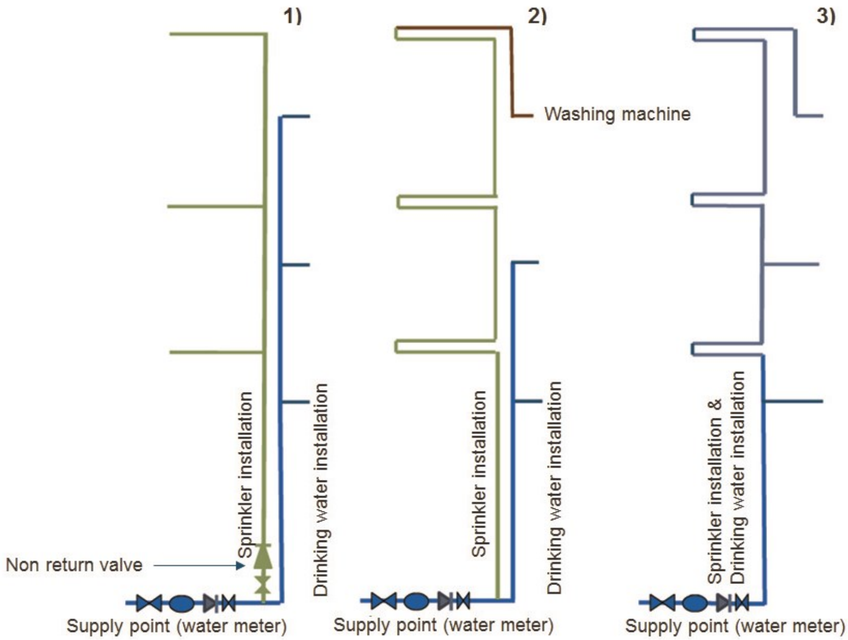

Figure 2-5 Approaches of fire sprinkler application: model 1 – separated system; model 2 – combined system; model 3 – integrated system.

Model 1 represents the approach in which a fire sprinkler system is separated from the domestic drinking water system. The connection between the DDWS and fire sprinkler system is equipped with a non – return valve. Theoretically, this approach poses no threat to the drinking water quality in DDWS. However, the disadvantage of the system would include regular testing of the valve, which would add to the maintenance costs of the system. Moreover the operability of the system can be compromised through accidentally closed valves. Model 2 is to a certain extent separated, but would have a limited flow through the sprinkler installations for a non-potable use, such as flushing a toilet. Major advantage of this system would consist of the inherent functionality: whereas each time the toilet is flushed, the functionality of the system can be tested, which minimises and almost excludes the danger of accidental closure of isolation valve. In Model 3 the sprinkler system is fully integrated into the domestic drinking water system, and, therefore, might have the most impact on the drinking water quality, but give maximum functionality.

2.4 DRINKING WATER SUPPLY IN THE NETHERLANDS

In the Netherlands, ten publicly-owned drinking water supply companies are responsible for raw water abstraction, treatment (from raw to drinking water) and distribution of drinking water. Those companies put the utmost priorities in providing adequate quantities of safe drinking water to their consumers without a residual disinfectant. The so-called “Dutch secret” includes various approaches, as follows.

- employing the best sources available, whereas 55% of water is abstracted from groundwater, 40 % from surface waters and 5% presents river bank or dune filtrate (Geudens 2015);
- applying the most efficient conventional and state - of – the art treatment technologies;
- preventing possible re-contamination during distribution phase, by maintaining the leakage rate low (< 3%) and avoiding very low or negative pressures;
- preventing re-growth of microorganisms, by production of biologically stable water (i.e. nutrient limited) and the biostable materials application (Van der Kooij 2000, 2003);
- optimization and maintenance of 115,000 km distribution network (self-cleaning networks and regular flushing of networks) (Vreeburg 2007, Vreeburg and Boxall 2007);
- statuary monitoring of produced and delivered drinking water.

These approaches put together have yielded a low average frequency of interruptions on average 7.5 minutes per connection per year (Van der Kooij and van der Wielen 2013), 99.9 % of samples which are in compliance with the Dutch drinking water standards (Inspectorate 2015) and a high level of consumer trust and satisfaction with regards to the drinking water quality, whereas over 95% of the Dutch population consumes drinking water from the tap (de Moel et al. 2006, Smeets et al. 2009).

2.4.1 Drinking water distribution systems

Once the raw water is treated and it meets drinking water quality standards, it is supplied through a network of pipes, stored in reservoirs and water towers and pumped, if necessary, to meet water demands and pressure requirements at the consumers’ taps .

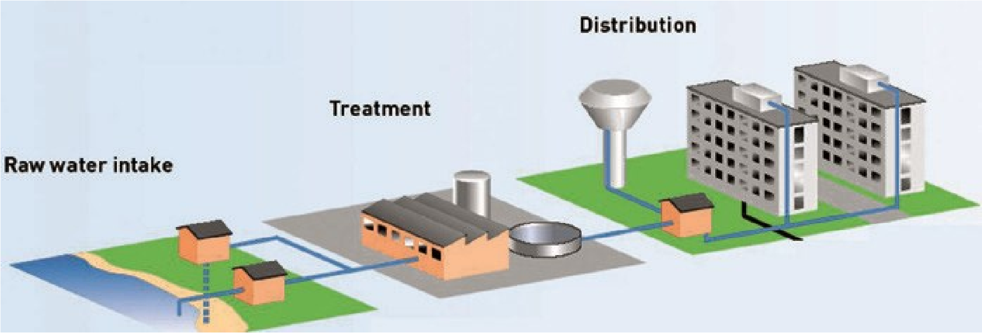

Figure 2-6 The drinking water supply chain (source: http://www.edgefxkits.com/blog/scada-system-architecture-types-applications/)

The drinking water networks contain complex interconnections of pipes with different diameters and capacities, including trunk mains (typical diameters ranging from 400 to 1540 mm), secondary mains (common diameters from 150 to 400 mm), distribution mains (typical diameters 32 – 200 mm), service pipes (~25 mm) and domestic drinking water installations (10 – 25 mm).

Sizing of the distribution networks requires detailed analysis and calculations due to the significant impact that every element has on the overall drinking water process. Historically, drinking water networks were dimensioned assuming the continuous growth of water demand and considering the philosophy "if in doubt, bigger is better", which led to the phenomenon of large networks. In addition to the projected, usually overestimated, water demands, fire flow requirements was an additional factor influencing the size of the pipes. Even though not strictly defined, the fire flow demand used to vary from 60 to 90 m3/h, while the maximum instantaneous flow for a single family house in the Netherlands used to be set at approximately 1.5 m3/h. It is important to mention that maximum instantaneous residential demand of 1.5 m3/h is calculated by the $q\sqrt{n}$ - method in the Netherlands, which was invented before 1954 (Blokker et al. 2006). The knowledge on individual demands of houses has only emerged in the last decade (Blokker et al. 2006), casting reasonable doubts on the validity of the $q\sqrt{n}$ – method. For instance, applying field measurements, Blokker and Van der Schee (2006) have shown that the $q\sqrt{n}$ - method is suitable for prediction of the maximum flows for one house or apartment. Still, the application of $q\sqrt{n}$ on a larger scale, for 200 apartments for instance, led to the overestimation of the maximum flow, implying that the flow used for sizing the distribution network may never happen, which in turns means that networks are oversized. Another important reason for oversizing the distribution networks was a prevalent application of looped networks, which was done for the perceived sake of the continuity of the water delivery to the consumers.

The impact of oversized networks is low velocities in the networks and extended residence times, which may promote accumulation of loose deposits and related water quality issues like discoloration, low disinfectant residual and microbiological regrowth (Vreeburg and Boxall 2007). To avoid problems associated with oversized networks, a novel concept of self-cleaning distribution networks was proposed (Vreeburg et al. 2009) with a reduced but realistic fire demand to 30 m^3/h. Self – cleaning networks are defined as a branched structure with smaller diameters and are sized using the following criteria: drinking water velocity of at least 0.4 m/s (for a few minutes a day) and the demand which was determined based on $q\sqrt{n}$ method (Vreeburg 2007). The costs of building self – cleaning networks are also 20% lower compared to the conventional looped networks.

In a recent research, a further step was taken with the respect to the extent of water demands and velocities of the self- cleaning networks. According to this research, in the peripheral zones of the distribution networks where the water flows appears to be highly variable, a stochastic demand model like SIMDEUM should be considered instead of the $q\sqrt{n}$ method. Results show that in those parts of the water supply networks, velocities in the range 0.2 – 0.25 m/s are enough to maintain clean pipes (Blokker 2010).

Design of domestic drinking water systems (DDWS), the part of the drinking water distribution system that includes the plumbing between the service pipes and consumers' taps, is mainly influenced by the type and lay-out of housing, the age of the DDWSs with respect to the piping materials, the type of house heating which determines the lay - out of the hot water plumbing (Moerman 2013). In addition to this, it is a common practice in many countries worldwide, that do-it-yourself labour carry out repair and installation work in DDWSs, which can greatly influence the design of the DDWSs (NRC 2006). Another feature of DDWSs which distinguish them from the rest of the distribution networks is that they are characterized by relatively lengthy sections of pipes with small diameters. A study in Columbia showed that DDWSs and service pipes had ~80% of the entire pipe length and ~25% of the overall surface area, and carried ~1.5% of the total volume in the overall water distribution system (Brazos et al.

1985). The impact of high surface area to volume ratio is seen in increased biological and chemical leaching, from biofilms which are formed all along the systems, and greater decay rates of the disinfectant residual (Brazos et al. 1985, NRC 2006, Rossman et al. 1994).

2.4.2 Drinking water safety

The definition of safe drinking water by the World Health Organization (WHO) is: “Safe drinking-water, as defined by the guidelines, does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages”(WHO 2011b). From a microbiological aspect, the definition means that water should not contain human pathogens. Chemically speaking, safe water should not have high levels of toxic chemicals or other toxic substances. Maximum allowed levels of toxic chemicals are defined by WHO guidelines or national standards for drinking water quality. Moreover, safe drinking water should be aesthetically appealing, with as low as feasible turbidity levels and without invertebrates in the water.

2.4.3 Factors affecting the water quality in the distribution phase

Drinking water quality changes during the distribution phase. Various factors are found to have an impact on quality of drinking water, such as pipe materials, hydraulics, residence time, temperature, etc.

Pipe materials

Common pipe materials used in distribution networks are cast iron, unlined or lined with bitumous or cementious coatings, asbestos cement, polyvinylchloride (PVC) and polyethylene (PE), while steel and concrete materials are generally used for the transport mains. In the drinking water distribution systems, materials that are commonly uses are copper, plastics (PVC or PE), galvanized steel, stainless steel and brass. All of the listed materials were found to leach substances into the water, through corrosion, dissolution and detachment. For instance, metal pipes are prone to corrosion – by which metal corrosion products are released into water (Sarin et al. 2004, Świetlik et al. 2012, Volk et al. 2000). The products of corrosion may be found in water in dissolved and particulate forms and if sufficient concentrations of particles are present, aesthetic problems can occur, such as higher turbidity and drinking water discoloration. The pipes made by synthetic polymeric materials, on the other hand, tend to leach odorous organic substances (Bruchet et al. 1999, Heim and Dietrich 2007, Tomboulian et al. 2004), that may lead to customer complaints with the respect to odour and taste. Synthetic polymeric pipe materials were also shown to release biodegradable organic compound, which can represent nutrient source for bacteria (Bucheli-Witschel et al. 2012).

Another phenomenon that is common for all pipe materials is formation of biofilms, as it is well known that micro-organisms can colonise any surface exposed to water. The characteristics of the pipe material may affect the densities and richness of biofilms. A few studies have shown that densities of biofilms are significantly higher on iron coupons than on plastic materials, while the densities of biomass fixed on PE and on PVC were similar (Niquette et al. 2000, Norton and LeChevallier 2000, Schwartz et al. 1998). Schwartz end co- workers reported the highest concentrations in biofilm formed on PE pipes, followed by stainless steel and PVC pipes, with the lowest in copper pipe (Schwartz et al. 1998). On contrary, a recent research revealed that the bacterial concentration in biofilms after 200 days of operation were in the same order for PE and copper pipes, and no differences in the microbial community structures were found (Lehtola et al. 2004).

Hydraulic regime

Changes in hydraulic regimes in drinking water distribution systems are often and they have an impact on interactions between water, sediments and biofilm. Periods with low water demand and oversized networks may result in low velocities, enabling particle sedimentation and providing a favourable environment for bacterial re-growth (Gauthier et al. 1999, Zacheus et al. 2001). During the hydraulic peaks which are the consequence of high water demands, fire-fighting actions or regular pipe flushing, detachment of biofilms and re-suspension of material deposited in pipes may happen (Lehtola et al. 2006, Vreeburg and Boxall 2007). DDWSs, on the other hand, are characterized by start and stop flow patterns. In DDWSs water velocities may be even 10 m/s, which can result in resuspension of sediments and detachment of the formed biofilms (NRC 2006).

Residence time

In the distribution networks residence is a function of pipe volume and the demand pattern and consequently may vary with distance to the treatment plant, water demands and diameter ranges in distribution networks. Long residence times, which may vary from 2 to 30 days depending on spread and lay out of the network, 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. Water stagnation in DDWSs promotes leaching of metals from pipes and fixtures (Lytle and Schock 2000b). Furthermore, in a pilot study that was carried out in Finland, it was reported that a stagnation time of 16 hours in DDWSs can lead to an increase in bacteria counts over one log unit (Lehtola et al. 2007) and a study from Germany revealed that overnight stagnation in DDWSs can stimulate overall microbial activity and richness, as well (Lautenschlager et al. 2010).

Temperature

Drinking water temperatures oscillate during the year because of the seasonal variations of the raw water temperature, especially if surface water is being used as a source. Typical drinking water temperatures in distribution systems range from a couple degrees in winter to 25°C in summer in the moderate climate of The Netherlands. Temperature represents one of the crucial factors to consider when assessing water quality, because of its effect on the chemical and microbiological processes within the distribution networks. In terms of chemical processes, water temperature is important due to its effects on metal solubility and the rate of corrosion, chlorine decay, disinfection efficiency, and formation of disinfection by-products. Higher drinking water temperatures have been related to enhanced bacterial richness and elevated numbers of indicator microorganisms, as coliforms, *Aeromonas* and heterotrophic bacteria (Francisque et al. 2009, LeChevallier et al. 1996c, Liu et al. 2013). The season itself has also been reported to affect the bacterial community abundance, as lower richness levels were detected in the winter and spring than in the summer (Pinto et al. 2014).

Once the drinking water is delivered to DDWSs, thermal equilibrium between stagnant water and surrounding air/walls takes place. The rate at which the drinking water is being warmed up to the room temperature is ~0.1°C per minute for a copper installation, meaning that only 2.5 hours are needed for water to be heated from 5 to 20°C in DDWSs during the winter months (assuming a room temperature of 20°C). Even though the water temperature plays a significant role in complex processes occurring between bulk water, pipe wall and biofilm little is known about its influence on water quality in DDWSs. In addition to this, no validated model is available for temperature prediction in DDWSs.

2.5 CONCLUSIONS

An automatic fire sprinkler system is an efficient approach to prevent fire damage and to bring down the number of fire causalities and injured. However, required operational hydraulic requirements, high flows and pressure, have made a commercial sprinkler system impossible to apply without additional infrastructure; such as pump and/or reservoir at the house level. A breakthrough in a design of a sprinkler head is, therefore, needed, in order to develop a system that can directly be connected to the DDWSs. One of the possible approaches is to redefine the sprinkler efficiency from hydraulic requirements towards the actual suppression efficiency, which should be done firstly by modelling and then by an experimental study on the spray characteristics. If the investigation shows that it is feasible to have satisfactory performance of the sprinklers under low flows and pressure, the second aspect that should be further tackled is the impact of the sprinkler implementation in DDWSs onto drinking water quality.

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CHAPTER 3

3 SPRINKLER SPRAY CHARACTERISTICS UNDER LOW-FLOW AND LOW-PRESSURE CONDITIONS

Abstract

An experimental investigation to explore the characteristics of the initial drop screen which was formed by sprinkler heads at low water pressures was carried out. Two commercially available sprinkler heads (with thin and massive frame arms) were modified, not only in terms of deflector plate design, but also with respect to the orifice diameter, in order to decrease the flow and study the effect on liquid sheet thickness, initial sheet angle, sheet breakup distance and drop size distributions and their correspondence with the existing mathematical models. It was found that the addition of a boss in the sprinkler design had little effect on the average drop size and sheet breakup distance. The presence of the boss was found to influence the initial angle of the liquid sheet, which was in line with findings of previous researches. Longer slots on the deflector plate did not change the initial angle of the sheet considerably, but did result in an earlier sheet breakup and smaller average drop diameter. A drop combustion sub-model was built, introducing novel parameters: Theoretical Heat Capacity (THC), Evaporate Heat Capacity (EHC) and Specific Heat Capacity (SHC), which could be used for estimating the actual heat capacity of the spray. In combination with the calculated drop size distribution in a spray screen, the combustion sub-model confirmed that sprinkler performance does not depend merely on provided flow, but rather on the drop size and the number of drops in a drop screen.

Keywords: Domestic fire sprinkler, spray characteristics, theoretical heat capacity, evaporative heat capacity

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3.1 INTRODUCTION

Worldwide, fires cause more than 10,000 deaths per year (Woodrow 2012), while home fires account for over 75% of all fire fatalities (FEM 2011). Among various technologies for reducing the burden of domestic fires, residential fire sprinklers have proven to prevent more than 80% of residential fire fatalities and around 70% of property damage per fire (NFPA 2012). Moreover, according to a recent study, fires in sprinklered dwellings have less negative environmental impact compared to non-sprinklered dwellings, as greenhouse gases released by burning dwellings could be significantly reduced when automatic sprinklers are activated (FMGlobal 2010).

The history of automatic fire sprinklers started with Philip W. Pratt's patent in 1872, while the first automatic sprinklers system was applied in practice in a piano factory in 1874 (Gorham 1919). Since then, automatic fire sprinkler has been defined as a device which is automatically activated when heated to a predetermined point, i.e. in case of a fire. Once the sprinkler is activated, a water stream is discharged through the sprinkler orifice. The water stream then strikes the sprinkler deflector, forming a spray which is delivered to a fire hazard area. To accomplish the goal of extinguishing or controlling a fire, not only must the formed sprinkler spray have sufficient momentum to penetrate the fire plume and reach the burning area, but it also must have adequate evaporative heat capacity (EHC) to adsorb heat from the fire plume and cool the surrounding environment. Therefore, the initial drop screen must consist of both large and small drops, since larger drops are better at penetrating fire plume and reaching more distant locations, while smaller drops have high heat adsorption capacity, and hence are more efficient in cooling the surrounding air (Sheppard 2002, Zhou and Yu 2011).

Even though the sprinkles have been widely used for more than a century, their application in Europe is mostly restricted to industrial purposes. Wide application in residential environments is still limited due to both technical and emotional issues (Vreeburg et al. 2012). The emotional issue of fire sprinkler restriction is the result of the so-called “Smoke detector” and “Hollywood” syndrome. ”Smoke detector” syndrome is associated with an alarm going off once in a while for no obvious reason, while “Hollywood” syndrome implies that if one of the fire sprinklers goes off, all of them will go off as well. However, in reality, only the sprinkler closest to the fire source will be heated and activated. The technical problem of wide spreading domestic fire sprinkler system implementation is more challenging. The core of the problem is the required water flow and injection pressure for conventional fire sprinklers, which is from 50 to 80 l/min and 0.7 to 1.6 bar, respectively. In the Netherlands, water flow and pressure at a household level are considerably lower (approximately 30 l/min and 0.5 bar, respectively, at the most distant location in a household). The required flow for a sprinkler system can never be supplied by a standard drinking water connection (Vreeburg 2007). Installation of a conventional sprinkler system would require a separate reservoir and a pump. Such a system should be maintained and tested regularly, which makes it very expensive and non-applicable on a large scale.

In the past five decades significant efforts have been made to experimentally and theoretically establish a correlation between design parameters of fire sprinkler systems and initial spray characteristics.

Figure 3-1 Design elements of a pendant sprinkler head (Zhou and Yu 2011)

Scaling laws Eq (3-1) for the sheet breakup locations and Eq (3-2) for the median drop diameter were firstly proposed by Huang (Huang 1970):

$$2r_{bu,sh}/d_0 = CWe^{-1/3} \quad (3\text{-}1)$$

$$d_{50}/d_0 = CWe^{-1/3} \quad (3\text{-}2)$$

where $r_{bu,sh}$ is the location at which the sheet is broken into ligaments and drops [m], d_{50} is the median drop size [m], d_0 is the orifice diameter [m], C is an experimentally found constant and We is the Weber number [-] ($We=\rho U^2 d_0/\sigma$, where ρ is water density [kg/m^3], U is velocity of water flow at the sprinkler orifice [m/s], d_0 is diameter of the injection orifice [m] and σ is surface tension of water-air interface [kg/s^2).

In order to evaluate the scaling laws, Dundas (Dundas 1974) used 6 sprinkler heads which were geometrically similar, but had different nozzle orifice diameters ranging from 3.1 – 25.4 mm and, with pressures ranging from 0.345 – 5.25 bar. Utilizing the high speed photographic technique, counting and measuring the size of drops by electronic scanner, he concluded that his experimental results were in line with the proposed $We^{-1/3}$ law.

Drop size measuring experiments were also performed by Yu (Yu 1986), but this time with a more sophisticated laser-based imaging technique. In this research, three upright sprinkler heads with different orifice diameters were used for measuring drop characteristics at two different locations, at 3 m and 6 m below the sprinkler heads. The results were also very much in line with $We^{-1/3}$ scaling law.

Sheppard and Widmann (Sheppard 2002, Widmann 2001) employed the Phase Doppler Interferometry (PDI) technique for measuring the spray characteristics of various sprinkler heads. Despite high accuracy of the PDI method, measurements could only be done at a single point and just a small sample volume was subjected to the analysis. When operating under pressures in the range from 0.93 to 2.0 bar, Widmann confirmed the scaling law of the previous researchers. However, at a low pressure of 0.69 bar, the local mean volume drop size was found to be considerably smaller than the one predicted by the scaling law. The influence of a much wider pressure range, from 0.345 to 5.52 bar, on drop characteristics was examined by Sheppard. Spray characteristics for 16 different sprinkler heads with different orifice diameters were measured by PDI technique at radial distance of 0.38 m from the sprinkler head. He stated that the correlation of the drop size to the Weber number was not applicable, most likely due to the limitations associated with the utilized PDI method.

Planar Laser Induced Fluorescence (PLIF) techniques were employed in Blum's study (Blum 2006) and the obtained results showed that the sheet breakup location for sprinklers with different types of deflector shape also followed $We^{-1/3}$ scaling law. It was also noticed that incorporation of the boss into the sprinkler design apparently increased sheet instability, and consequently the sheet breakup distance became significantly shorter.

Ren continued Blum's research (Ren 2010) and reported that the sheets formed by the sprinkler with a commercially available deflector broke up earlier than the sheets generated by the flat deflected sprinkler at a comparable orifice diameter. The detected behaviour was most likely a result of geometrical features which had been added to the flat deflector. This may have resulted in formation of the considerably thinner sheet at the edge of deflector, and hence smaller drop sizes.

Based on the free surface boundary layer (Watson 1964) and wave dispersion theories (Dombrowski and Johns 1963), a deterministic model of the atomization process was developed by Wu (Wu et al. 2007). Assuming a flat deflector plate, the sprinkler was modeled as an axisymmetric impinging jet. At high injection pressure ranges, the fit between the predicted and measured data was found to be outstanding. However, at low pressure conditions (below 0.69 bar) large discrepancies were found between the modeled outputs and experimental data.

Liquid sheet thickness in the deterministic model, developed by Wu (Wu et al. 2007),was calculated using the Eq (3-3) derived by Watson (Watson 1964):

$$\delta = \frac{d_0^2}{8r} + 0.0166\left(\frac{7\vartheta}{U_0}\right)^{1/5} r^{4/5} \tag{3-3}$$

where d_0 is the orifice diameter [m], r is the radius of the deflector plate [m], v is water kinematic viscosity [m^2/s] and $U_0$is the average jet speed from the orifice [m/s].

In a recent study (Zhou and Yu 2011), an integrated model has been developed so that the sheet thickness could be determined for different degrees of viscous interaction with the deflector. In this model, both sheet thickness (∂) and velocity of the water sheet at the deflector edge (U) can be numerically solved using the Eq (3-4) and Eq (3-5) with unknown starting thickness and sheet velocity.

$$\delta \frac{dU}{dr} + U\frac{d\delta}{dr} + \frac{\delta}{r}U = 0 \tag{3-4}$$

$$2U\delta r\frac{dU}{dr} + U^2\delta = -rg\delta\frac{dU}{dr} - \frac{1}{2}C_d r U^2 \tag{3-5}$$

where g is the acceleration of gravity [m/s^2], C_d is the average friction coefficient of the deflector plate [-].

The results of the sheet thickness were found to correspond well with the data obtained experimentally under very low pressures (0.034 bar and 0.069 bar). Additionally, in this study the average drop sizes were experimentally derived under low injection pressures (0.34 bar and 0.68 bar). However, the drop diameters were measured only at horizontal distances from the edge of the disk of 0.3 and 0.6 m, which were not necessarily areas of the initial sprinkler spray formations.

These experimental studies were mostly conducted under higher pressure ranges. These pressures made widespread application in domestic applications impossible. In the study described in this chapter, an experimental study was carried out at low injection pressures, which were available in drinking water installation at household level in the Netherlands at the most distant location in a house. In order to assess the influence that the sprinkler geometry, under these circumstances, had on the key parameters of the atomization process, detailed measurements of sheet thickness, initial angle of the liquid sheet, sheet breakup distances and drop size distributions were performed.

Even though the Fire Dynamics Simulator (FDS), a computational fluid dynamics model of fire-driven fluid flow, is becoming increasingly popular lately (Ren 2010), this research has developed two novel parameters based on the characteristics of a spray. In a combustion sub-model built based on (Strahle 1993) these two parameters, Theoretical Heat Capacity (THC) and Evaporate Heat Capacity (EHC), can be calculated. Both parameters demonstrate the ability of a water spray to adsorb heat, whereas THC depends only on the mass flow of the formed spray, while EHC also includes the influence of a drop diameter onto drop lifetime.

3.2 MATERIALS AND METHODS

3.2.1 Experimental setup

Two commercially available fast-response residential fire sprinklers (Tyco Series LFII Residential Sprinklers) with differently shaped frame arms, thin and massive, were modified (see Figure 3-2)

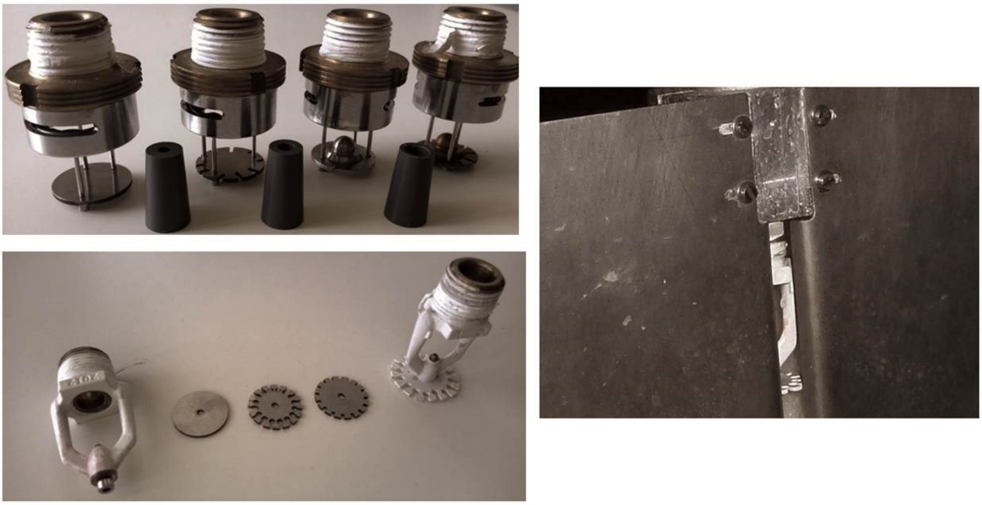

Figure 3-2 Sprinkler configurations applied for flow visualization and drop parameters measurement. Upper left photo: Fast response sprinkler with thin frame arms, circle flat (Flat), slotted (Tined), flat deflector with a boss (Bossed) and commercially available geometric of residential fire sprinkler (Commercial) and orifice implants (diameter of orifice:3, 4.5 and 6mm). Down left photo: Fast response sprinkler with massive frame arms, circle flat (Flat), deflector with long slots (Long Slots), deflector with short slots (Short slots) and commercially available geometric of residential fire sprinkler (Commercial. Right photo: metal flow splitters attached around sprinkler head.

Two sprinkler configurations were chosen in order to assess the influence of frame arms on key parameters of the formed spray. Modification of the sprinkler heads was made not only in terms of altering the geometry of the deflector plates (Figure 3-2), but also with respect to the diameter of the sprinkler orifice. Since a previous research (Zhou and Yu 2011) had confirmed that the deflector diameter had little impact to overall initial spray characteristics, deflector plates of different shapes, but with the same diameter (23.6 mm), were fabricated for this study. As for the sprinkler head with thin arms, the plates were designed as the Flat deflector, Tined deflector and Bossed deflector.

In a recent study (Zhou and Yu 2011) the influence of slot width on average drop diameter has been analyzed, but the previous studies had not investigated the impact of slot length on spray characteristics. Therefore, for the sprinkler head with massive frame arms, the deflector plates were fabricated as the Flat deflector, the deflector with Short slots and the deflector with Long slots. For both sprinkler heads, special PVC orifice implants were manufactured with inner diameters of 3 mm, 4.5 mm and 6 mm (Figure 3-2, upper photo) to restrict the flow.

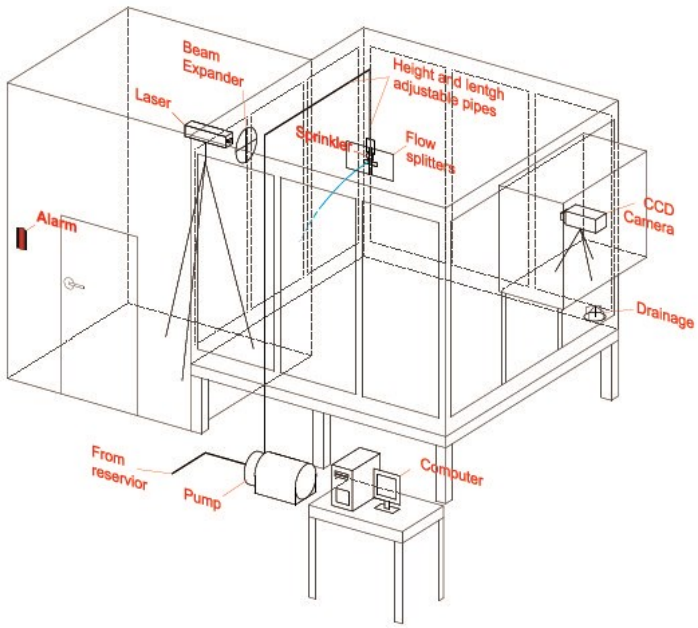

Figure 3-3 Experimental rig

As shown in Figure 3-3, experiments were carried out in a closed 2.5 m x 2.5 m 2.0 m room with a drainage system. Sprinkler heads were mounted to the copper pipeline with inner diameter of 20 mm. To allow longitudinal and vertical movement of the sprinklers, the pipes were made of smaller pieces (l= 50 mm), which corresponded to the average camera field of view.

Water was supplied to the sprinkler head by a pump which provided flow rates of up to 50 L/min. In order to physically separate flow stream which entered the camera field of view for flow visualization, metal flow splitters with adjustable slot, were designed and fabricated. The splitters' slot was shaped in a way to minimize the influence of flow separation on a spray pattern (see Figure 3-2). The splitters were installed around the sprinkler head, 5 mm from the deflector plate, and in order to protect splash entering the field of view, a sponge was attached to the outer region of flow splitters.

A pressure sensor and a temperature probe, both with analog outputs, were installed close to the sprinkler. Local measurements were carried out at injection pressures of 0.35, 0.5, 0.7 and 1 bar at various horizontal distances (0, 50, 100, 150, 200, 250, 300 and 350 mm from the deflector edge), elevation angles (0º, 15º, 30º, 45º, 60º, 75º and 90º) and azimuthal angles (0º, 15º, 30º, 45º, 60º, 75º and 90º); where 0º azimuthal angle was defined at frame arms location, while 0º elevation angle was at the horizontal level of the deflector (Figure 3-3).

Flow visualization and drop characterization were performed employing the Shadowgraphy method which was a non-intrusive, imaging technique manufactured by La Vision Company. The shadowgraphy system consisted of a CCD camera, double pulsed laser, high efficiency diffuser and Davis 8.1.1 software. Davis 8.1.1 (Lavision GmbH, Goettingen, Germany) was an accurate and efficient data acquisition and visualization software which contained ParticleMasterShadowgraphy unit for determining the size, velocity and shape of the individual particles (drops) (ParticleMaster Shadow, 2013).

The CCD camera used in this research was La Vision Imager Pro X 2M CCD camera with CCD resolution of 1600x 1200 pixels. To increase the magnification factor, the camera was fitted with a Sigma Macro 180 mm, f/2.8 lens spaced on extension rings. The source illumination was provided by a Litron double pulsed laser with output energy of 200 mJ at a wavelength of 532 nm. The pulsed laser light was delivered to a high efficiency diffuser which created the uniform background illumination. The discharge of the laser and capture rate of the camera were set by a programmable time unit in order to acquire double images.

The imaging system was firstly spatially calibrated using a ruler which was set up in the image region. Calibration included taking a single frame with the CCD and corresponding the distance on the ruler to the pixel resolution. The average image region size of the camera included a field of view of 72.36 mm x 54.27 mm. Since the depth of view is a size dependent value (bigger drops have larger depth of view than smaller drops), the depth of view was calibrated using the circles which were drawn on the ruler (diameters from 0.5 to 6 mm). The ruler was mounted in imaging region and was traversed in and out of the focal plane, and based on measurements depth of view was correlated to the circle/drop diameter as dof = 29.87 d.

For each sprinkler configuration, flow visualization was done at 0, 50, 100, 150, 200, 250 and 300 mm horizontal distance from the deflector edge. Firstly, a reference/baseline image with no water flow was captured, followed by at least 50 pairs of images taken at aforementioned measurement locations. To assure stable results of the spray parameters, at least 50 pictures were analyzed for each sprinkler configuration. For the present research, sheet breakup distance was defined as a location where the liquid sheet was completely torn into drops and calculated using the X and Y coordinates in the Davis software.

One of the most important drop diameters, which provides statistical information in spray analysis, is the volume median drop diameter, d_{v50}. Volume median diameter indicates that 50% of the cumulated volume consists of drops with diameters smaller than d_{v50}. In present study, drop size measurements were carried starting from 0.5 m from the deflector plane, as at that region spray was considered to be fully atomized.

The cumulative volume distribution (CVF_k) was calculated by integrating measurements of different i_{th} azimuthal and j_{th} elevation locations, using Eq (3-6) (Turns 2000, Yu 1986):

$$\mathrm{CVF_k} = \frac{\sum_{i=1}^{n_i}\sum_{j=1}^{n_j} A_{i,j} v_{i,j} \mathrm{CVF}_{i,j,k}}{\sum_{i=1}^{n_i}\sum_{j=1}^{n_j} A_{i,j} v_{i,j}} \qquad (3\text{-}6)$$

where n_i and n_j are the number of measurement locations in the azimuthal and elevation directions, $A_{i,j}$ is the i,j_{th} measurement area [m^2] and $v_{i,j}$ is the volume flux [Lpm/m^2].

The volume flux, in present research, was not measured by mechanical collection, but was calculated using Eq (3-7):

$$v = \sum_{i=1}^{N} \frac{1}{6} \frac{\pi u_i d_i^3}{A * dofi} \qquad (3\text{-}7)$$

where N is the number of detected drops [-], d_i is an individual drop diameter [m], A is the measurement area [m^2], u_i is the drop velocity related to the drop size [m/s],and d_{ofi} is the corrected depth of view [m].

Moreover, the influence of water temperature onto the atomization process was examined in this research. One sprinkler configuration, with commercially available components and an orifice diameter of 6 mm, was employed in the experiments and drop parameters were measured at water temperatures of 17, 20, 25, 30 and 35°C. Water temperature was increased by mixing cold water (T = 17°C) and hot water (T = 70°C) in a 200L volume container from which water was pumped to the existing sprinkler pipeline. A temperature probe with analog output was installed in the pipe close to the sprinkler head for the purpose of water temperature monitoring.

3.2.2 Drop combustion sub-model

A drop combustion sub-model was built based on (Strahle 1993) taking into account the following assumptions:

- the evaporating drop is present in a quiescent medium;
- the burning is a quasi-steady process;
- the ambient pressure is uniform;
- interaction with other drops is not taken into account;
- radiation heat transfer is neglected.

The outcomes of the combustion sub-model are two novel parameters: Theoretical Heat Capacity (THC) and Evaporate Heat Capacity (EHC). Theoretical heat capacity (THC) accounts for the amount of heat per unit time that is necessary for the heating and phase change of water flow from liquid to dry saturated steam. Calculation of THC [kW] was done using the Eq (3-8)

$$\mathrm{THC} = (\mathrm{h_S} + \mathrm{h_L})\mathrm{N_{drop}} \qquad (3\text{-}8)$$

where h_s is the amount of heat required for the phase heating [J], h_L is the amount of heat that is necessary for the phase change [J] and N_{drop} is a number of drops in a drop screen per time unit [1/s]. THC [kW] shows theoretical ability of water spray to absorb heat or energy and is related to the mass flow of drops.

The other parameter, Evaporative Heat Capacity (EHC) [kW] is the amount of heat per unit of time required for the phase change of a single drop and is thus dependent upon the actual drop size.

The evaporation rate [kg/s] of one drop is calculated by Eq (3-9):

$$m_{ev.drop} = \frac{4\pi k_g r_s}{c_{pg}} \ln\left(B_q + 1\right) \tag{3-9}$$

where: k_g is gas-phase thermal conductivity [W/(m·K),], r_s is drop radius [m], c_{pg} is gas phase specific heat [J/(kg·K)] and B_q represents a dimensionless transfer number [-]. In order to simplify the calculations, parameters k_g and B_q are considered to be constant.

The evaporation rate of water drops is determined by Eq (3-10):

$$m_{ev} = m_{ev.drop} \cdot N_{drop} \tag{3-10}$$

To determine the ratio between the evaporation rate of water drops and the overall mass flow (MF [kg/s]), coefficient η is introduced and calculated using Eq(3-11). η determines the part of mass flow (MF) that is used for an evaporation process [%].

$$\eta = \frac{m_{ev}}{MF} \cdot 100\ \% \tag{3-11}$$

EHC represents the portion of THC value that is used for the evaporation process of a drop screen and is therefore calculated employing Eq (3-12):

$$EHC = \eta \cdot THC \tag{3-12}$$

At standard atmospheric pressure, hot and stagnant air is considered for the current model. Assumed ambient air temperature is 200^{0}C, since it is the average air temperature value of a room in the case of a medium fire.

3.3 RESULTS AND DISCUSSION

3.3.1 The initial angle of the liquid sheet

The initial angle of the liquid sheet is the angle between the liquid sheets, as it leaves the deflector, and the horizontal. It represents one of the most important parameters in the modeling of the sheet trajectory. So far, no good models for predicting the initial angle (Ren 2010) have been available and therefore the sheet angle has to be experimentally derived. In this research, the shadow imaging system is applied to visualize and study the initial sheet angle. The results are given in Figure 3-4 and Figure 3-5. For the sprinkler configuration with minimal orifice diameter (3 mm) and under operating pressure of 0.35 bar, the data set was incomplete and is not presented in the following Figure 3-5.'

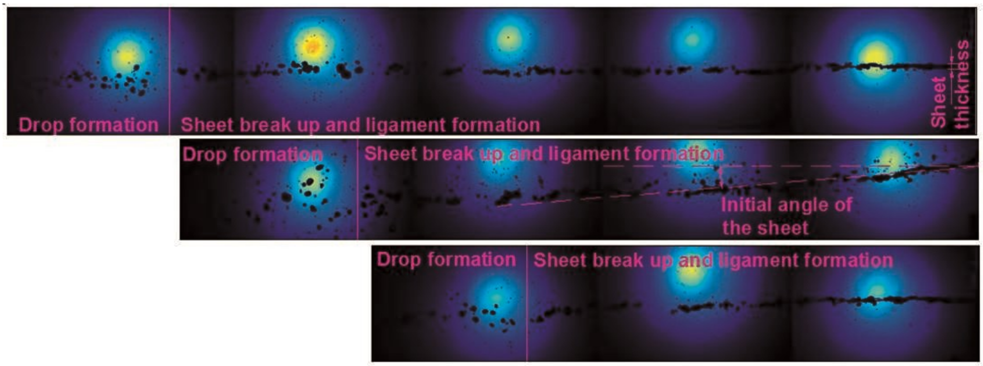

Figure 3-4 Test photo: Upper photo: Flat deflector; Middle photo: Bossed deflector; Bottom photo: Tined deflector with orifice diameter d_o = 4 mm, at 0.5 bar operating pressure

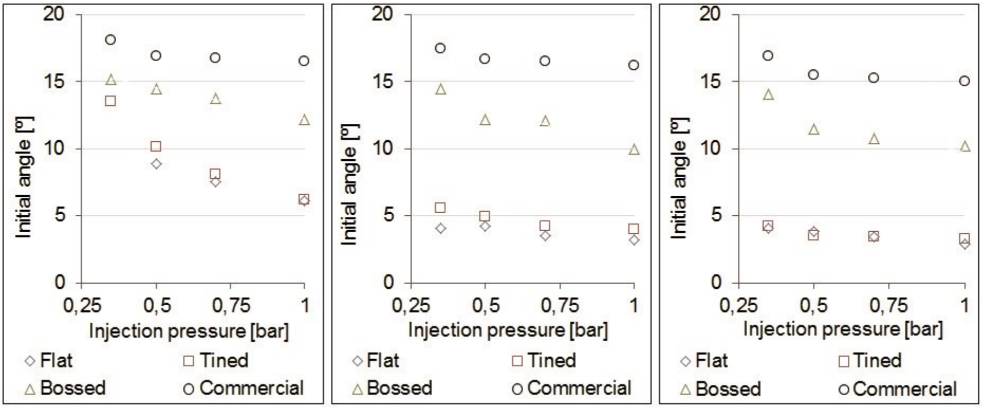

Figure 3-5 Average measurements of the initial sheet angle for the sprinkler head with different geometrical features. Left: Measurements for the sprinkler head with orifice diameter d_0= 3 mm. Middle: Measurements for the sprinkler head with orifice diameter d_0= 4 mm. Right: Measurements for the sprinkler head with orifice diameter d_0= 6 mm

Figure 3-5 clearly shows that the decrease in initial angle of the sheet is a direct result of the increase of the injection pressure for all sprinkler configurations. The liquid sheet produced from the nozzle with a flat deflector and orifice diameters of 4.5 and 6 mm has the average initial angle of only a few degrees, 3.8° and 3.6° respectively. Larger initial angles (average 7.5°) are measured for the sprinkle with the orifice diameter of do=3 mm. In addition, sheet bending has been observed for the nozzles (do=3 mm) under the lowest applied pressure (0.35 bar). This is most likely due to the pronounced influence of surface tension and gravity, which tend to bend the sheet upon itself under low pressure conditions i.e. for small Weber number (Trefethen 1966).

The average initial angle of the sheet delivered by the tined deflector plate has been 9.5° for sprinkler with 3 mm orifice diameter, and 4.7° and 3.6° for the nozzles with orifice diameters of 4.5 and 6 mm, respectively. Therefore, the addition of the slots in sprinkler geometry appears to have limited impact on the initial angle of the liquid sheet, which is in line with previous findings (Blum 2006, Zhou and Yu 2011). As in the previous case, sheet curvature is noticed when the smallest orifice diameter (d_0=3mm) and the lowest injection pressure of 0.35 bar have been applied.

On the other hand, the presence of a boss in the sprinkler configuration has been found to increase the value of the initial angle of the liquid sheet, up to approximately 12.5°. This is expected since a recent research (Zhou and Yu 2011) has reported that the boss tends to direct the sheet toward the sprinkler centerline.

The commercial deflector plate used in this research has had both boss and slots incorporated into its design. The largest values of the initial sheet angle have been measured for the nozzle with this type of deflector plate, and are in the range of 15° to 18.1°.

3.3.2 Thickness of the liquid sheet

The thickness of the sheet is the second most important parameter which is required for the sheet trajectory modeling. Sheet thicknesses were measured at 5 mm distance from the flat deflector plates, at the position vertical to the frame arms. Detailed measurements of the sheet thicknesses have been carried out under injection pressures of 0.5 bar and 0.7 bar, for the orifice diameter of 6 mm and results are presented in Table 3-1.

Table 3-1 Sheet thicknesses measured at 5 mm from the edge of the flat deflector (deflector radius r=11.8 mm)

Injection pressure	0.5 bar	0.7 bar
Sheet thickness	δ[mm]	δ[mm]
Thin frame arms configuration	1.35	1.45
Massive frame arms configuration	1.29	1.42

As evident from Table 3-1, very similar measurements of sheet thickness have been obtained for two differently shaped sprinkler heads. On the other hand, the increase of operating pressure has resulted in ~ 10% thicker sheets at the 5 mm from the edge of the plate.

Assuming that the change of sheet thickness in the first 5 mm from deflector plate is negligible, the experimental results of sheet thickness are compared to data obtained using the deterministic model (Zhou and Yu 2011) and Zhou model for the sheet thickness (Zhou and Yu 2011).The comparison between measured and calculated values is shown in Figure 3-6.

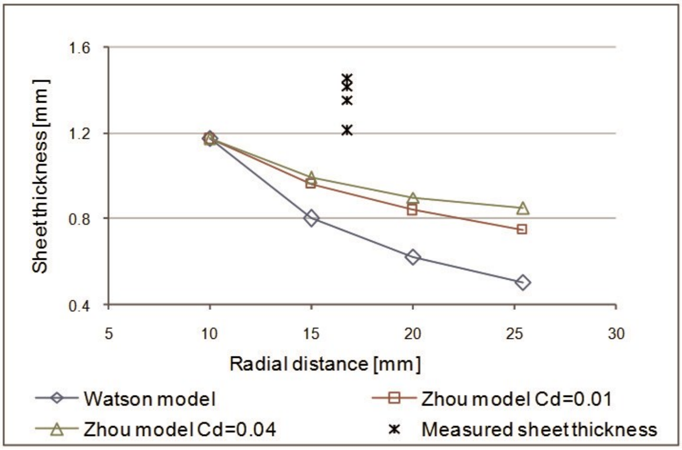

Figure 3-6 Comparison between calculated and measured sheet thicknesses

As shown in Figure 3-6, the sheet thicknesses, calculated using the Watson model is underestimated for the given injection parameters. The sheet thicknesses, predicted using the Zhou's integral model, for the friction coefficients of 0.01 and 0.04, are only slightly closer to the real set of data. As explained by the authors of the integrated model, at a constant friction coefficient, the thickness predictions made with the integrated thickness model appear to be insensitive to the velocity of the sheet. In reality, however, as the sheet velocity decreases approaching the edge of the deflector plate, the value of friction coefficient varies, and therefore for more reliable model outputs velocity dependent friction coefficients should be taken into account.

3.3.3 Sheet breakup distances

The breakup distance of the liquid sheet is the distance at which the sheet is completely broken up into drops. The experimental results of the sheet breakup distances are summarized Figure 3-7 and Figure 3-8.

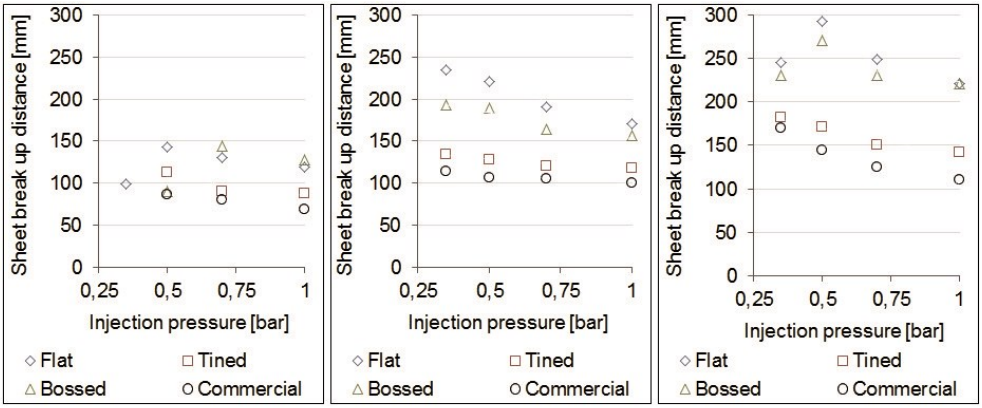

Figure 3-7 Breakup distance of the liquid sheets for the fast response sprinkler with thin frame arms. Left: Measurements for the sprinkler head with orifice diameter d0= 3 mm. Middle: Measurements for the sprinkler head with orifice diameter d0= 4 mm. Right: Measurements for the sprinkler head with orifice diameter d0= 6 mm

For all examined sprinkler configurations, the distance of sheet breakup distances decreases with the increase of the discharge pressure, which is in line with the findings from previous researches. Figure 3-7 shows that the addition of a boss on the deflector has had little effect on sheet breakup distances, since the average shortening of the sheet delivered by the bossed plate, is estimated to 7.8%. As soon as the slots have been incorporated into the deflector shape, a certain volume of water is directed between the tines, resulting in the thinner and more unstable liquid sheet along the slots. This stream has been found to breakup more readily, with the average shortening factor of 32.0%. Naturally, the presence of both slots and boss (commercial shape of the deflector plate) in the sprinkler geometry is expected to have the largest effect on the sheet breakup distances, since the water jet is forced downwards between the tines by the boss component. As anticipated, the average shortening of the sheet delivered by the commercial plate has been found to be most pronounced, i.e. 42.7%.

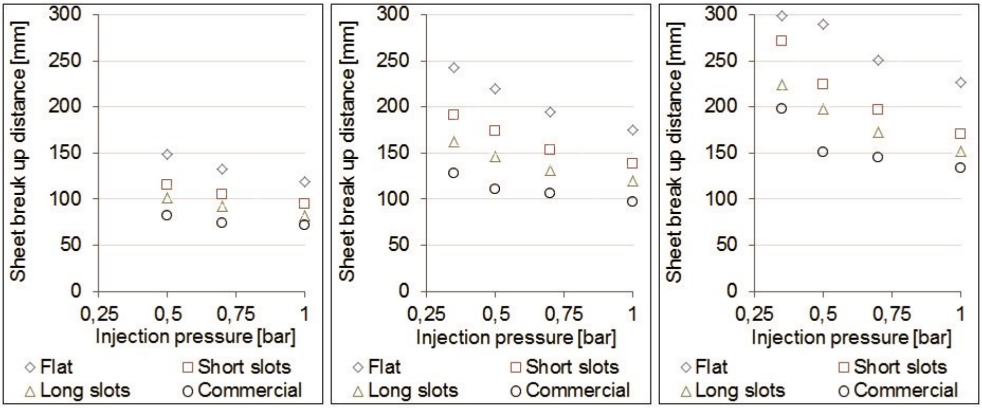

Figure 3-8 Breakup distance of the liquid sheets for the fast response sprinkler with massive frame arms. Left: Measurements for the sprinkler head with orifice diameter d_0= 3 mm. Middle: Measurements for the sprinkler head with orifice diameter d_0= 4 mm. Right: Measurements for the sprinkler head with orifice diameter d_0= 6 mm

Figure 3-8 shows the sheet breakup distance for the sprinkler configurations with flat deflector, deflector with short slots, deflector with long slots and commercially available elliptic deflector plate. It can be noticed that short slots have considerably smaller influence on breakup distances than the other two sprinkler configurations. The average measured shortening is 21.9%. As for the sprinkler configurations with long slotted and standard commercial deflector plates, the sheet has been found to breakup faster i.e. the median shortening has been 32.3% and 44.6%, respectively.

Scaling laws for the for the sheet breakup locations (see Eq 3-1) were firstly proposed by Huang (Huang 1970). In the Eq (3-1), C represents the constant which is experimentally derived and is dependent upon sprinkler configuration.

The results of this study show that the sheet breakup locations at 0.5, 0.7 and 1 bar operating pressure follow better $We^{-1/4}$ than $We^{-1/3}$ scaling law for all sprinkler configurations. However, at the lowest injection pressure of 0.35 bar, scaling laws are inapplicable. Table 3-2 summarizes experimentally derived constants.

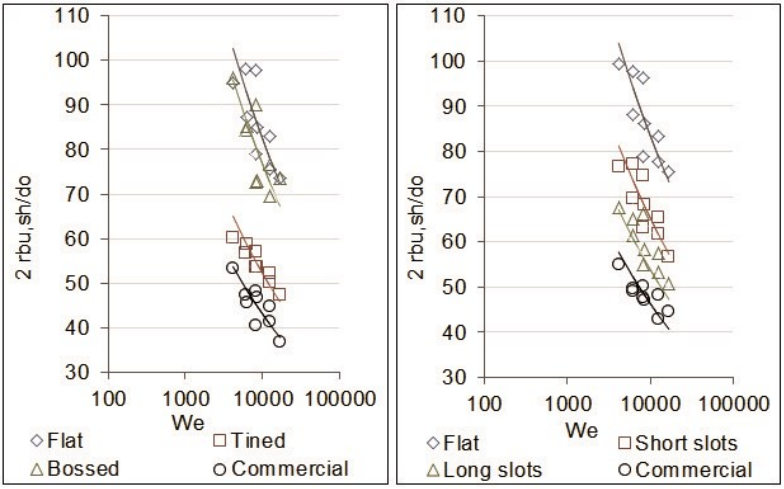

Figure 3-9 Breakup distances at various injection pressures correlated with the We number for sprinkler configurations with thin frame arms (left) and massive frame arms (right)

Table 3-2 Experimentally derived constant C for sprinklers with different geometrical features

Geometry	Deflector	Flat	Tined	Bossed	Commercial
Thin frame arms	C	824	522	767	431
Geometry	Deflector	Flat	Short slots	Long slots	Commercial
Massive frame arms	C	834	652	538	463

3.3.4 Average drop diameter

The average drop diameter of the initial sprinkler spray is derived applying the Davis 8.1.1 module -ParticleMasterShadowgraphy. As found in literature (DeBoer 2002) , the stable drop diameter never goes above 6 mm in sprinkler sprays, while the minimum size of drop that was detected in this research was ~0.05 mm. Therefore, when applying Davis software, the upper threshold value for the drop size is set at 6 mm, and the lower threshold was 0.05 mm.

Measurements of the average drop diameter for different sprinklers configurations are presented in Figure 3-10 and Figure 3-11. The same pattern of decrease of the overall drop diameters with the increase of the injection pressure has been observed for all investigated sprinkler configurations.

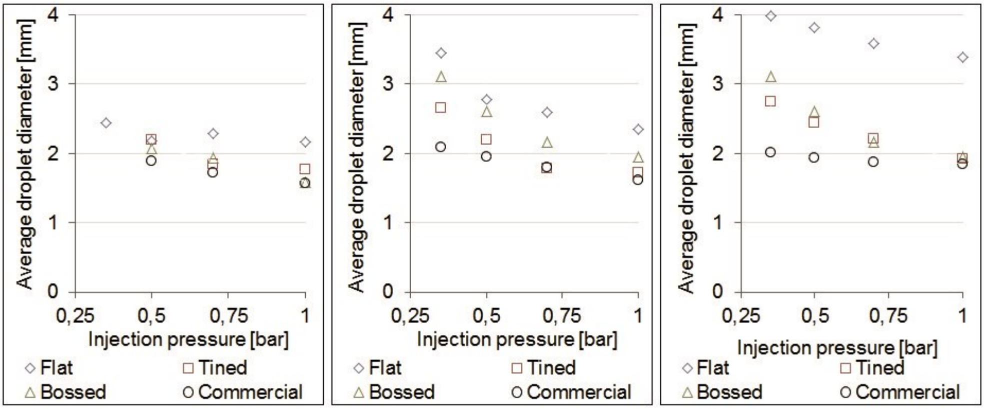

Figure 3-10 Average drop diameter for the fast response sprinkler with thin frame arms. Left: Measurements for the sprinkler head with orifice diameter d_0= 3 mm. Middle: Measurements for the sprinkler head with orifice diameter d_0= 4 mm. Right: Measurements for the sprinkler head with orifice diameter d_0= 6 mm

Figure 3-10 shows that, among the other geometrical features incorporated in the flat design of the deflector, the bossed deflector has minimal effect on the average drop size, since up to ~24% of difference between the flatted and bossed drops has been measured. As for the tined deflector nozzle, the measured drop size is up to ~30% smaller than the drops produced by the flat sprinkler's deflector. As expected, the addition of both boss and slots (commercial deflector) into flat deflector design has increased the complexity of the drop formation and thus, the initial drop diameter has been up to ~ 40% smaller.

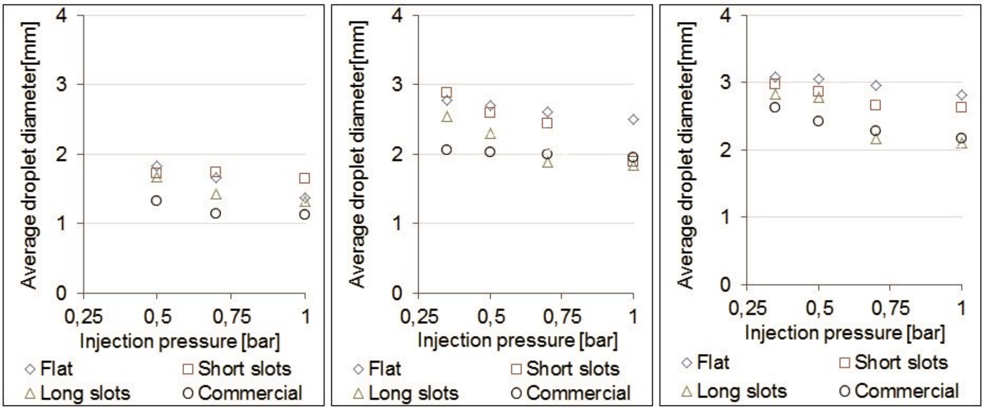

Figure 3-11 Average drop diameter for the fast response sprinkler with massive frame arms. Left: Measurements for the sprinkler head with orifice diameter d_0= 3 mm. Middle: Measurements for the sprinkler head with orifice diameter d_0= 4 mm. Right: Measurements for the sprinkler head with orifice diameter d_0= 6 mm

As shown in Figure 3-11, the average drop diameters produced from the deflector with short and long slots are only up to 5% and 15%, respectively, which is lower compared to the drop diameters of the flat deflector plate. By employing the commercially available deflector shape, this difference has been more pronounced and is up to 30%.

Though the same trend of decrease in drop diameter, when one or more geometrical features are incorporated in sprinkler design, was reported in other studies (Blum 2006, Ren 2010, Zhou and Yu 2011)the median drop diameter in present study, is found to be larger than those earlier reported. A possible reason for large median drop diameter is that volume flux was calculated using the shadowing information, instead of being mechanically measured. Because of the high spray density at some measurement locations, the shadows of some drops may overlap and thus two or more smaller drops might be identified as a single drop Therefore, the volume fluxes calculated by the shadow-imaging system might be lower up to ~ 25% than the real volume fluxes, as reported in a recent research (DeBoer 2002),which would directly influence the calculated median diameter.

As for the sheet break up locations, for all investigated nozzles, results show reasonable agreement with $We^{-1/4}$ scaling laws, for the operational pressures 0.5, 0.7 and 1.0 bar (still, for the lowest injection pressure of 0.35 bar, scaling laws were not applicable). Experimentally derived constants are given in Table 3-3.

Table 3-3 Experimentally derived constant C for sprinklers with different geometrical features

Geometry	Deflector	Flat	Tined	Bossed	Commercial
Thin frame arms	C	6.1	4.3	4.4	4.0
Geometry	Deflector	Flat	Short slots	Long slots	Commercial
Massive frame arms	C	5.1	4.9	4.2	3.9

The experimental measurements of drop size have been compared to the outputs obtained from the deterministic model. The comparison between measured and calculated values is given in Figure 3-12.

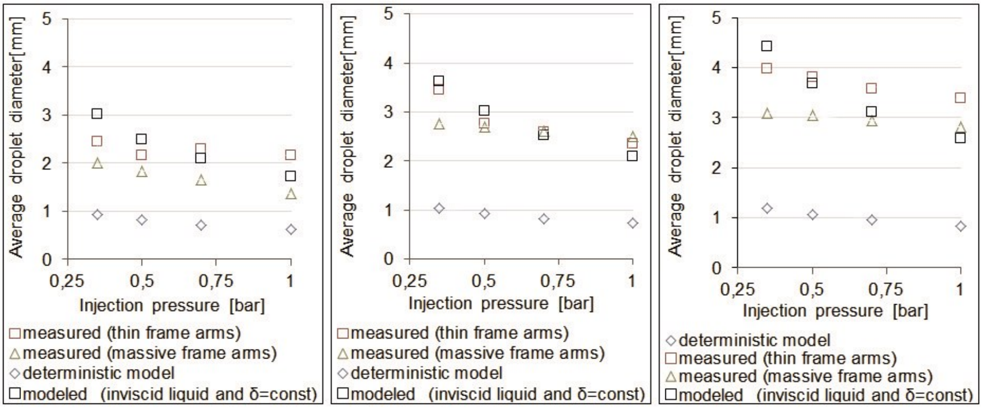

Figure 3-12 Comparison between measured and modeled drop diameter for sprinkler with flat deflector. Left: comparison for the sprinkler head with orifice diameter d_0= 3 mm. Middle: Comparison for the sprinkler head with orifice diameter d_0= 4 mm. Right: Comparison for the sprinkler head with orifice diameter d_0= 6 mm

Figure 3-12 shows that average drop diameter decreases with increasing pressure, indicated both by the model and measured data. However, the average drop diameters, calculated using the approach of attenuating sheet, are found to be considerably underestimated when compared to the experimental results. Though unexpected, if the assumption of inviscid liquid with uniform sheet thickness (Dombrowski and Johns 1963) is considered for calculations, the model achieves good quality prediction performance. Still, such good model performance is only applicable for the simplified configuration of the sprinkler head with flat deflector shape. As soon as the tines or boss have been implemented into the sprinkler geometry, poor agreement between the modeled and measured data is observed.

3.3.5 Influence of frame arms

Previous researches (Blum 2006, Ren 2010, Zhou and Yu 2011) reported that presence of the frame arms had increased the complexity of the atomization physics. However, very limited data on the influence of the arms onto initial spray characteristics have been available nowadays. In this exploratory study, the impact of the frame arms onto initial trajectory of the sheet and average drop size are studied.

As stated above, in order to investigate the impact of the frame arms onto spray characteristics, two sprinkler heads with different designs of the arms, thin and massive (see Figure 3-2) were chosen.

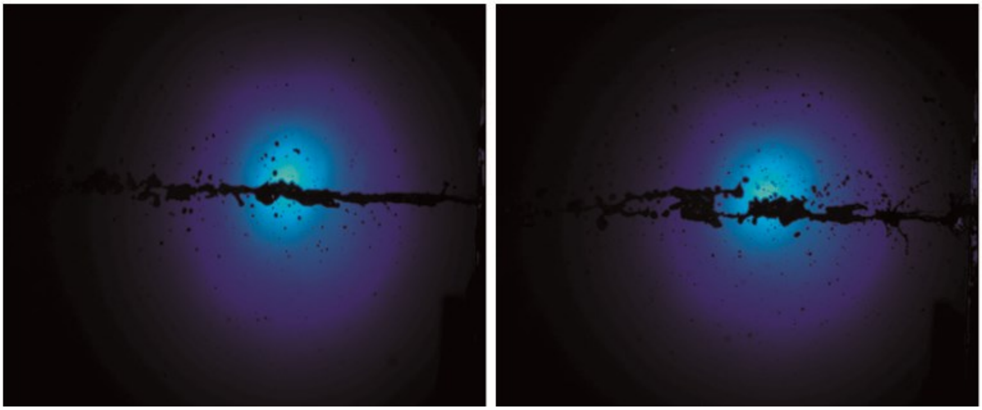

Figure 3-13: Sheet leaving the flat deflector of the sprinkler with thin frame arms. Orifice diameter d_0=6 and injection pressure of 0.5 bar. Left: Sheet formed between frame arms. Right: sheet formed behind the frame arms (after striking the frame arm)

Figure 3-13 shows that very thin frame arms have minimal impact on the initial trajectory pattern of the sheet. The average drop size of the initial spray formed under the influence of the frame arm has been determined at the injection pressure of 0.5 bar. According to the obtained results ~35% of smaller drops have been formed under the influence of the thin frame arm.

Figure 3-14 shows the influence of massive frame arms on the sheet trajectory pattern.

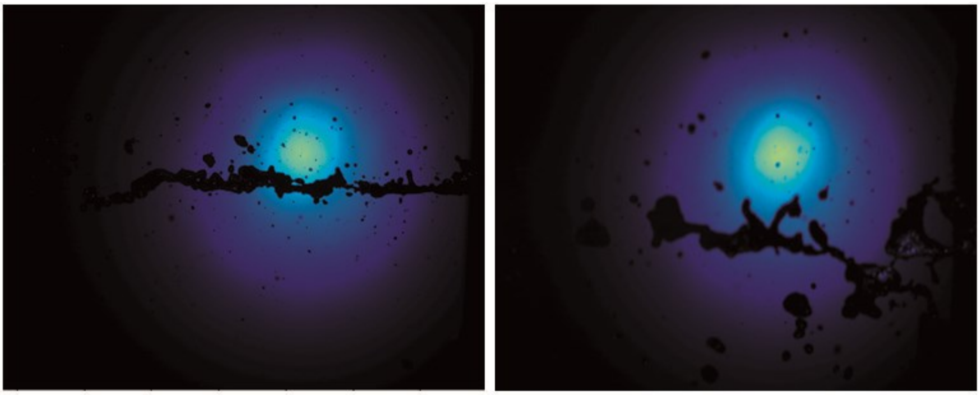

Figure 3-14 Sheet leaving the flat deflector of the sprinkler with massive frame arms. Orifice diameter d_0=6 and injection pressure of 0.5 bar. Left: Sheet formed between frame arms. Right: sheet formed behind the frame arms (after striking the frame arm).

It is clear from Figure 3-14 that the presence of massive frame arms has affected the trajectory of the sheet. The possible explanation for this could be that once the liquid sheet strikes the massive frame arms, water loses its energy. Since a portion of kinetic energy has been spent during the strike, only a part is left for the sheet to continue moving forward. Even though the coverage area influenced by massive frame arms has not been assessed, it has been observed that only when the influence of the frame arms is being measured, wetting of the surrounding glass walls of the container is never achieved. This implies that the spray formed in the region of massive frame arms might not be able to reach more distant locations.

In addition to the above stated, experimental results shown in Figure 3-10 and Figure 3-11 for the Flat deflector may give an insight into the influence that frame arms have on the average drop diameter. The average diameter of the drops produced from the sprinkler with massive frame arms is up to 25% larger than the one obtained with thin frame arms configurations. This leads to the conclusion that adding the massive frame arms into sprinkler's geometry considerably enhances the complexity of the spray formation process.

3.3.6 Influence of water temperature on average drop diameter

Water temperature in inner installations is almost always equal to the room temperature, and thus varies from season to season. As the viscosity decreases with rise in water temperature, the influence of water temperature on the overall drop size has been examined. The average drop diameter obtained under different water temperatures ranging from 17 - 35°C are shown in Table 3-4.

Table 3-4 Influence of water temperature onto average drop diameter

Temperature	17°C	20°C	25°C	30°C	35°C
d_{v10} [mm]	0,786	0.789	0,77	0,777	0.720
d_{v50} [mm]	1.477	1.457	1.463	1.446	1.384
d_{v90} [mm]	1.868	1.856	1.838	1.838	1.856

It is obvious from Table 3-4 that temperature of water plays an insignificant role in the drop formation process. This has been expected since, according to the deterministic model, only 2% of decrease in drop diameter is predicted by increasing the temperature of water from 17°C to 35°C.

3.3.7 Theoretical and evaporative heat capacity of a drop screen

As a starting point, measured drop size distributions for sprinkler with the same, commercially available deflector, design but different orifice diameters (6 mm and 11.1 mm, respectively) have been incorporated in the combustion sub-model. Table 3-5 presents measured and calculated parameters for both sprinklers.

Table 3-5 Outputs of the combustion sub-model

Parameter	Symbol	Unit	Modified Sprinkler	Commercial Sprinkler
Design parameters				
Orifice diameter	d_o	[mm]	6	11.1
Deflector radius	r_{def}	[mm]	11.8	11.8
Pressure	Δp	[bar]	0.5	0.5
Flow	Q	[L/min]	17	49.5
Assumed coverage area	A	[m^2]	19.6	41.7
Measured parameters				
Diameter corresponding to 10% cumulative	D_{10}	[mm]	1.06	1.8
Parameter	**Symbol**	**Unit**	**Modified Sprinkler**	**Commercial Sprinkler**
Diameter corresponding to 50% cumulative	D_{50}	[mm]	2.02	2.75
Diameter corresponding to 90% cumulative	D_{90}	[mm]	3.12	3.68
Calculated from real data set				
Theoretical Heat Capacity	THC	[kW]	417	980
Evaporative Heat Capacity	EHC	[kW]	127	295
Specific Heat Capacity	SHC	[kW/m^2]	6.5	7.1

Table 3-5 clearly shows that, even though hydraulic performance for the two sprinkler heads differs in terms of heat capacity, the difference is not directly proportional to the flow. According to the combustion sub-model results, the residential sprinkler operating with a flow of 17 L/min might still deliver around 90% of the specific heat capacity [SHC] of the sprinkler operating with a flow of 49.5 L/min. However, the coverage area of the low flow sprinkler is expected to be smaller and hence, more sprinklers per unit of area would be required, which will eventually lead to the faster activation of the sprinkler head and possibly to better firefighting performance.

3.4 CONCLUSION

In this experimental study, evaluation of the initial spray characteristics affected by sprinkler design parameters (such as orifice diameter, deflector and frame arms shape) has been carried out under low pressure range, which is available in the drinking water installations in the Netherlands, at most distant locations in a house. The experimental results reveal strong connection between the sprinkler geometry and initial spray characteristics, under given operational conditions. Good agreement between calculated drop size and actual drop size measurements has been found when an assumption of inviscid liquid and uniform sheet thickness is made for the sprinkler with flat deflector design. As soon as the geometrical features, such as tines and boss, have been incorporated into sprinkler geometry, the model fit to the data is not entirely satisfactory.

Measured drop size distribution has been incorporated in the combustion sub-model. As expected, the outputs of the combustion sub-model indicate that the overall sprinkler performance is not directly proportional to the provided flow and pressure, but is contingent upon the drop size and the number of the drops in a screen. However, a smaller portion of the area can be effectively covered under lower flows, and therefore, more sprinkler heads per area are required to ensure the containment of the beginning fire in its initial stage. Though the present study is focused on low pressure conditions which correspond to operational thresholds in the Dutch inner installations, introduced THC, EHC and SHC parameters from the combustion sub-model might be used as a rapid experimental tool for water sprays, regardless of the range of operating pressures.

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CHAPTER 4

4 A TEMPERATURE MODEL FOR DOMESTIC DRINKING WATER SYSTEMS

Abstract

Domestic drinking water supply systems (DDWSs) are the final step in the delivery of drinking water to consumers. The factors that distinguish DDWSs from the distribution mains are the length of residence time, change in water temperature, surface area to volume ratio and loss of disinfectant residual. Temperature is one of the rate controlling parameters for many chemical and microbiological processes and is, therefore, considered as a surrogate parameter for water quality processes within the drinking water distribution phase. In this study, a mathematical model is presented that predicts temperature dynamics of the drinking water in DDWSs. Two full-scale DDWSs were built and run according to one year of stochastic demands with a time step of 10 seconds. The drinking water temperature was measured at each point-of-use in the systems and the data set was used for model validation. The temperature model adequately reproduced the temperature profiles, both in cold and hot water lines, in the full scale DDWSs. The model showed that inlet water temperature and ambient temperature have a large effect on the water temperature in the DDWSs.

Keywords: drinking water, domestic systems, water temperature, modelling, calibration, validation

This chapter has been submitted for publication as: Zlatanovic, L., Moerman A., van der Hoek, J. P., Vreeburg, J.H.G., Blokker, M. Development and validation of a drinking water temperature model in domestic systems

4.1 INTRODUCTION

The domestic drinking water system (DDWS) is defined as the part of the drinking water distribution system that includes plumbing between a water meter and consumer's tap, and thus, represents the final section of a drinking water supply system. Apart from being made from a wide range of materials that are not commonly present in the distribution mains (copper, brass, high density polyethylene, stainless steel), the factors that additionally distinguish DDWSs from the distribution mains are the magnitude of residence time, temperature gradient, surface area to volume ratio and loss of disinfectant residual (NRC 2006).

Among the above mentioned factors, temperature is one of the crucial parameters that influences the quality of drinking water. The significance of drinking water temperature is based upon its role in physical, chemical and biological processes. Viscosity of drinking water, for instance, tends to fall as temperature increases. A rise from 5 to 25°C causes the viscosity to drop by almost 40% resulting in a decrease in flow resistance, which affects the transport phenomena in pipes (Blokker and Pieterse-Quirijns 2013). Chemically speaking, water temperature is important due to its effects on copper solubility, the rate of corrosion, lead leaching from brass fixtures, bulk chlorine decay rate and formation of disinfection by-products. Higher water temperatures aggravate the corrosion of pipes. As an example, an increase in water temperature to 60°C in copper pipes results in nearly three times higher copper levels (Boulay and Edwards 2001, Singh and Mavinic 1991). Leaching of brass may significantly be increased by temperature rise leading to increased lead levels that leached from brass elements (Sarver and Edwards 2011). Bulk chlorine decay rates have also been found to increase with temperature, and the chlorine decay coefficient in water was reported to increase more than threefold when temperature goes from 10 to 20°C (Li et al. 2003). In case of the presence of the organic precursors in drinking water, formation of chlorination by-products, as trihalomethanes (THMs), is inevitable. In a study on THMs formation it was concluded that levels of trihalomethanes increased considerably with elevation of water temperature (Li and Sun 2001). Water temperature is known to promote biological processes, as biological activity increases 2 fold when temperature increases by 10ºC (Van der Kooij 2003). Higher water temperatures also encourage bacterial regrowth and coliform occurrence during the water distribution phase (LeChevallier et al. 1996a, LeChevallier et al. 1996b).

Given the substantial impact that temperature may have on water quality, the World Health Organization recommends a maximum value of 25°C for drinking water (WHO 2006). In the Netherlands, where drinking water is being distributed without persistent disinfectant residual, the temperature of drinking water at the customers' tap is not allowed to exceed 25°C. However, as stated in a recent study (Blokker and Pieterse-Quirijns 2013), during a relatively warm year (2006), 0.1% of the samples did exceed the legislative limit.

Even though the drinking water temperature has been recognized as one of the most important parameters that affects the drinking water quality, most research on modelling of water quality in distribution systems have considered water temperature to be constant (DiGiano and Zhang 2004, Rubulis et al. 2007). In a recent study, a model that predicts the temperature of the water in distribution networks was proposed (Blokker and Pieterse-Quirijns 2013). To our knowledge, the temperature dynamics have not been modelled yet for the DDWSs. In this research a model, intended to predict the temperature dynamics in DDWSs, was developed and validated.

4.2 METHODOLOGY

4.2.1 Model development

Temperature model

The temporal change of water temperature inside the pipes is governed by the difference between water temperature and ambient temperature. Calculation of the temperature change over the time step Δt can be done by solving the energy balance equation for a control volume with arbitrary length Δx:

$$E_{T,t+\Delta t} - E_{T,t} = \Delta E_T \qquad (4\text{-}1)$$

where $E_{T,t}$ and $E_{T,t+\Delta t}$ [J/m] symbolize the amount of thermal energy in the control volume at time t and time t+Δt, respectively, while ΔE_T represents the change of thermal energy in the control volume over the time interval Δt. By introducing the geometry of the control volume and physical properties of water, the differential equation is generated:

$$\frac{dT}{dt} = \frac{4h_{overall}}{\rho c_p D}(T_\infty - T) \qquad (4\text{-}2)$$

where T is the actual temperature of water, which is averaged over the pipe diameter, [K], T_∞ is the ambient temperature [K], $h_{overall}$ is the overall heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$], ρ the water density [$kg \cdot m^{-3}$], c_p the heat capacity of water [$J\ kg^{-1}\ K^{-1}$] and D the pipe diameter [m].

To obtain the overall heat transfer coefficient, it is essential to establish the different heat transfer processes that occur along the pipe. These processes can be divided into three phases: convective heat transfer phase inside the pipe ($R_{conv,1}$), conductive heat transfer phase through the pipe wall (R_c) and convective heat transfer phase outside the pipe ($R_{conv,2}$). The heat transfer phases can be modelled based on the concept of thermal resistances in series (see Figure 4-1).

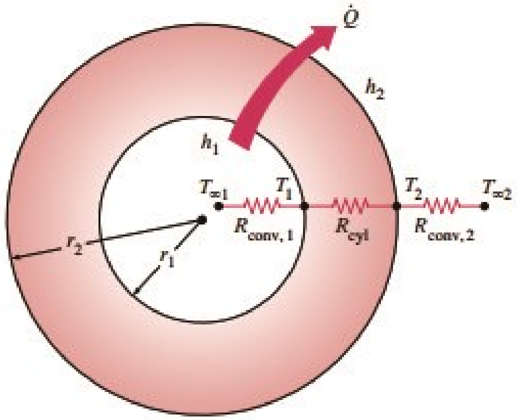

Figure 4-1 Thermal resistance network for a pipe (Cengel 2002)

The overall thermal resistance can be described as equation (4-3):

$$R_{overall} = R_{conv,1} + R_c + R_{conv,2} \quad (4\text{-}3)$$

The overall heat transfer coefficient can be related to the overall thermal resistance and can be defined as shown in equation (4-4).

$$h_{overall} = \frac{1}{\frac{1}{h_{water}}+\frac{1}{h_{out}}+\frac{1}{h_{wall}}} \quad (4\text{-}4)$$

The variables h_{water}, h_{out} and h_{wall} are the heat transfer coefficients for the inner (h_{water}) and outer pipe surface (h_{out}) and the pipe wall (h_{wall}) in $W \cdot m^{-2} \cdot K^{-1}$ (Cengel 2002).

The heat transfer coefficient for the inner surface of the pipe is calculated as (Cengel 2002):

$$h_{water} = \frac{\lambda_w Nu_w}{D} \qquad (4\text{-}5)$$

where λ_w symbolizes the water thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$] and Nu_w is the Nusselt number for water.

Depending on the flow conditions (stagnant, laminar or turbulent), the value of the Nusselt number changes (Janssen and Warmoekserken 1991).

$$Nu_w = \begin{Bmatrix} Re < 10 & 5.8 \\ 10 < Re \le 2300 & 3.66 \\ Re > 2300 & 0.023Re^{0.8}Pr^{1/3} \end{Bmatrix} \qquad (4\text{-}6)$$

where Re is Reynolds number and Pr is Prandtl number.

The heat transfer coefficient for the outer surface of the pipe can be calculated by equation (4-7):

$$h_{out} = \frac{\lambda_a Nu_a}{D} \qquad (4\text{-}7)$$

where λ_a is the thermal conductivity of air [$W \cdot m^{-1} \cdot K^{-1}$] and Nu_a is the Nusselt number for air.

The Nusselt number for air can be calculated using the Rayleigh number (Ra), which is equal to the product of the Grashof (Gr) and the Prandtl (Pr) number:

$$Nu_a = \alpha R_a^{\gamma} = \alpha(G_r P_r) \qquad (4\text{-}8)$$

where α and γ are coefficients which are experimentally obtained. All pipes are treated as vertical plates in this research and α=0.59 and γ=0.26 (Cengel 2002).

The Grashof number can be calculated as (Cengel 2002):

$$G_r = \frac{g\beta(T_\infty - T_s)G^3}{v^2} \qquad (4\text{-}9)$$

where g is the acceleration of gravity [$m \cdot s^{-2}$], β is the thermal expansion coefficient of air [K^{-1}], T_s is the temperature at the outer pipe wall surface [K], v is the kinematic viscosity of air [$m^2 \cdot s^{-1}$] and G is the length [m] of the characteristic geometry. Since the characteristic geometry is positioned perpendicular to the direction of the gravity force, for vertical pipes the characteristic geometry is equal to the pipe length, while for horizontal pipes G is considered to be equal to the pipe diameter.

The heat transfer coefficient for the wall of the pipe can be derived using the equation (4-10)

$$h_{wall} = \frac{\lambda_p}{d_p} \quad (4\text{-}10)$$

where λ_p represents the pipe thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$] and d_p is the thickness of the pipe wall [m], which is considered to be 10% of the pipe diameter in this research.

While water flows in pipes, air flow develops around the pipes, and thus, Nusselt numbers are averaged along the characteristic geometry for which the Nusselt number equals (Cengel 2002):

$$Nu_a = 0.59\ R_a^{0.25} \quad (4\text{-}11)$$

Substituting equations (4-5), (4-7) and (4-11) in equation (4-4) and assuming d=0.1D we end up with the equation (4-12):

$$h_{overall} = D(\lambda_w^{-1} {Nu_w}^{-1} + 0.1\lambda_p^{-1} + \lambda_a^{-1} {Nu_a}^{-1}) \quad (4\text{-}12)$$

Hydraulic model

To model the temperature dynamics in DDWSs it is essential to have: 1) information on the lay-out of the system to be modelled, in terms of pipe diameters, lengths of pipes and pipe materials; 2) a set of demand patterns for each tap point in the systems; 3) a hydraulic simulation software 4) an extension to the hydraulic software to implement the equations from the temperature model.

In this research, the layout of the conventional DDWS was done according to a plan of a terraced house, so-called Typical Dutch House (Figure 4-2 left), as terraced houses account for approximately 60% of all residential properties in The Netherlands (as cited in Majcen et al. 2013).

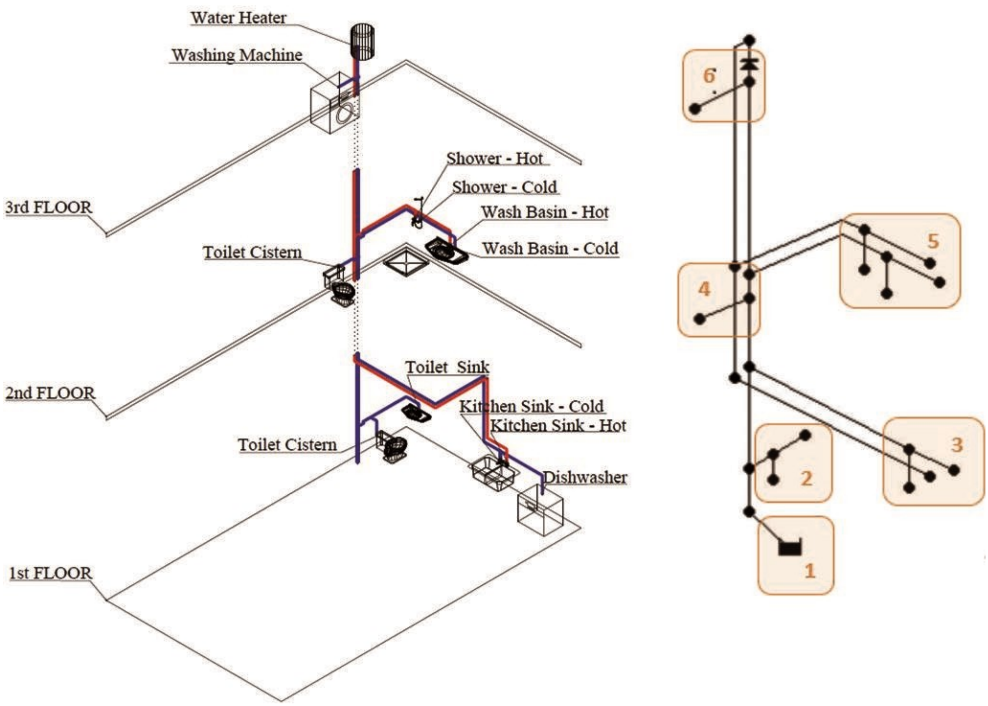

Figure 4-2 Left: Axonometric scheme of the conventional DDWS system according to a plan of the Typical Dutch house. Right: Conventional DDWS model in EPANET. 1-Water meter, 2-Guest toilet taps (toilet cistern and sink), 3-Kitchen taps (sink cold/hot water and dishwasher), 4-WC - Toilet cistern, 5- Bathroom taps (shower cold/hot and sink cold/hot water), 6-Washing machine tap.

The demand patterns were generated by SIMDEUM (**SIM**ulation of water **D**emand, an **E**nd **U**se **M**odel) for a 2 person household. SIMDEUM, developed by KWR Watercycle Research Institute (Nieuwegein, The Netherlands), is a stochastic model which is grounded on statistical information of water appliances and water consumers. SIMDEUM generates water demand patterns based on consumers' behaviour, considering the differences in DDWSs and water-appliances (Blokker et al. 2010, Blokker et al. 2006). In total, 365 different demand patterns for a two person household (including 104 weekend patterns) were generated.

Modelling the hydraulics within the DDWSs was done by applying a free water distribution system modelling software EPANET. EPANET was developed by the United States Environmental Protection Agency (EPA) in 1993 (Rossman 2000). The simulation outputs provide hydraulic information such as, flows in pipes, pressures and water residence times at various locations the systems.

An extension to EPANET called EPANET-MSX (**M**ulti-**S**pecies e**X**tension), was used to implement the temperature model equations. This extension applies a Lagrangian time-based approach, i.e. ‘follows’ the trajectory of water parcel throughout the system and considers concentrations, in this case temperature, as a function of time and their prior coordinates.

4.2.2 Model validation

Experimental rig

To validate the temperature model (and to study the influence of the DDWS’s extension for fire sprinklers system integration on water quality), two full-scale test rigs were built using standard copper pipes. One experimental rig was built in a way to resemble a conventional DDWS (Figure 4-2), while the other was constructed with the extension of the plumbing for the residential sprinkler accommodation (Figure 4-3).

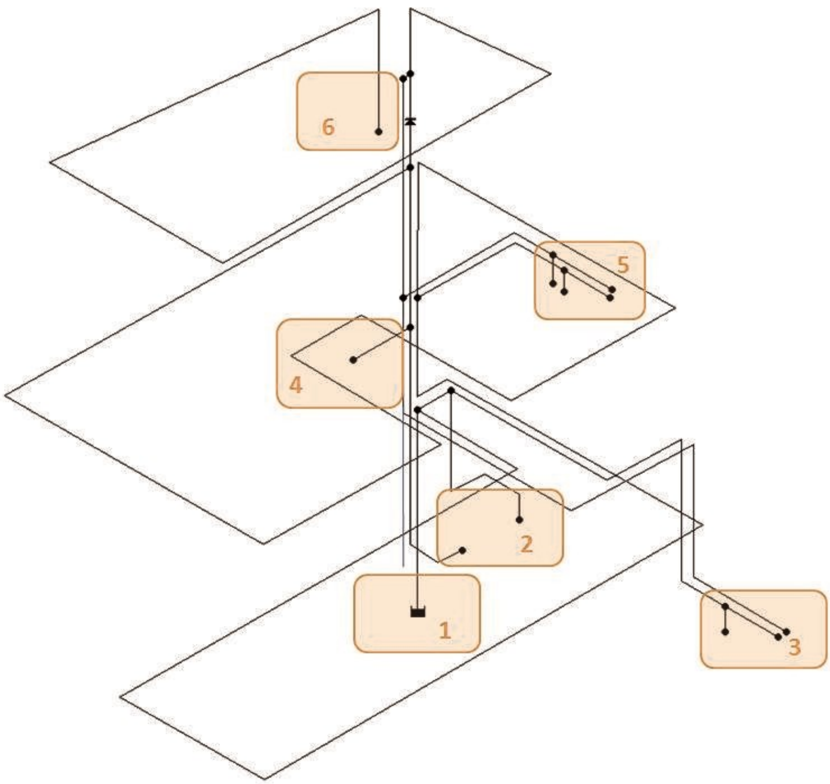

Figure 4-3 Extended DDWS model in EPANET. 1-Water meter, 2-Guest toilet taps (toilet cistern and sink), 3-Kitchen taps (sink cold/hot water and dishwasher), 4-WC - Toilet cistern, 5- Bathroom taps (shower cold/hot and sink cold/hot water), 6-Washing machine tap.

Configuration of the conventional experimental rig, complies with the Dutch home plumbing codes NEN 1006 (NEN1006 2002). The conventional DDWSs consisted of 2 vertical lines and 4 horizontal branches of copper (manufactured in accordance with European Standard EN 1057), namely vertical copper composite of 22 mm diameter - carrying cold water to the upper floors, vertical copper tube of 15 mm (ID) –delivering hot water from a 50 L water heater and copper tubing's of 15 mm- supplying cold and hot water from the vertical lines to the 11 plumbing fixtures (solenoid valves), as given in Figure 4-4 . The total length of the pipes was 48.6 m in the conventional system and the volume of the plumbing rig was 6 L. The extended system has additional loops of 22 mm diameter piping on each floor, and the total length of the piping in the extended system was 116 m and the volume was ~26 L.

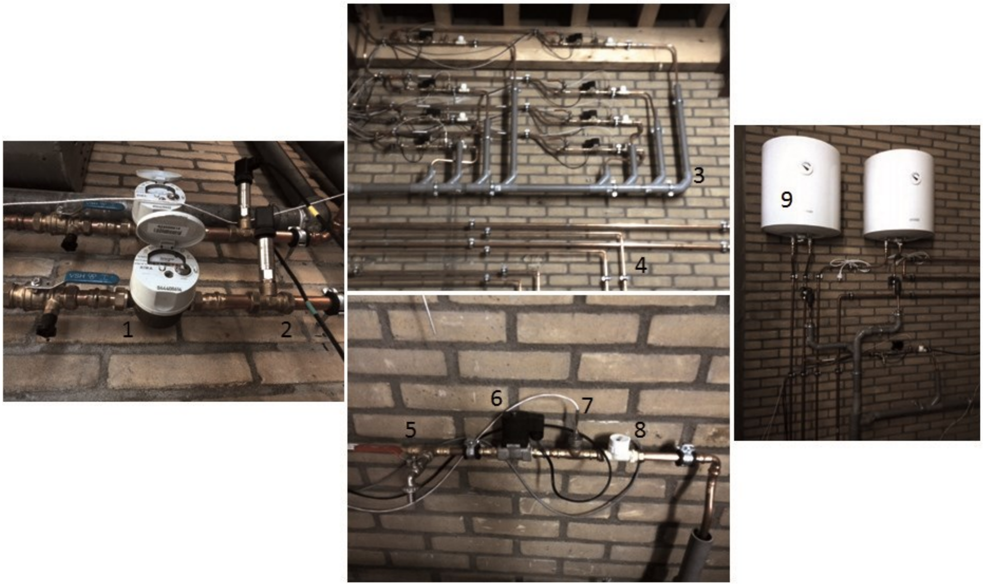

Figure 4-4 Test rigs. 1 - Water meters, 2 - Pressure sensors 3 - Copper supply pipes, 4 - PVC drainage pipes 5 - Sampling tap 6 - Solenoid valve, 7 - Flow sensor, 8 - Temperature sensor, 9 - Water heaters

Water consumption pattern

To be able to mimic a realistic drinking water consumption at the household level, the test rigs included 11 solenoid valves (point of use) per system. The valves were configured to run automatically ("on" and "off" mode) according to one year demand patterns with a time step of 10 seconds, which were generated by SIMDEUM model. For the sake of validation of the temperature model, a SIMDEUM pattern for a weekend day (Saturday) was used. In Figure 4-5 the measured flows are given.

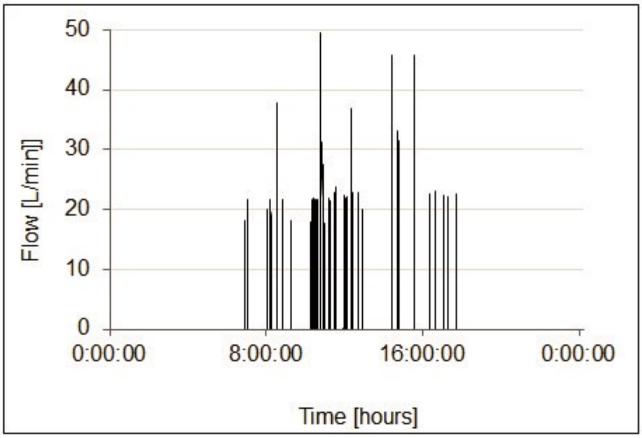

Figure 4-5 Measured day pattern for all points of use in the conventional DDWSs on a weekend day (Saturday)

In the DDWS experimental rig, the magnetic valves operated only in “on” and “off” mode. This means that the valves were either fully open or fully closed, which is not common in real DDWSs. In addition to this, in experimental DDWSs opening a tap to the full extent took longer than in real water systems (from “off” to “on” mode - the magnetic valve response is 0.1 – 4s). What was also specific for the experimental set – up is that all magnetic valves were of the same discharge capacity of 4 tapping units (TU), where capacity of 1 TU is equal to 5 L/min. Having a slow response and the same capacity for all valves in the systems resulted in larger discharge on the weekend day, as the total measured daily water use was 1000 L.

The length of the pipe that delivers water from the connection point to the lab rigs is 40 m. Despite the fact that the pipe has been thermo-insulated, stagnant water in the pipe heated up by 2.5°C per hour, until it got equal to the ambient temperature. For the purpose of model validation, the 40 m long pipe was flushed for 5 minutes before the opening of each tap in the system. This was done in order to ensure a stable inlet water temperature profile, for the purpose of drinking water temperature model validation.

Every point of use in the systems was equipped with a flow sensor and a temperature probe. In addition to this, a temperature sensor was mounted before the water meters, to measure the inlet water temperature. Also, three ambient temperature sensors were installed on every “floor “of our virtual Typical Dutch House. Before starting the experiments, all sensors were manually calibrated. The drinking water temperatures, ambient temperatures and flows were continuously measured, every 10 seconds. The ambient temperature around the pipes was also manually measured three times a day during the “model validation” day . The control of the solenoid valves and data logging was achieved by using the data acquisition, control and analysis software LabView (Manual 1998).

Overview of the input parameters

The overview of the parameters used to validate the temperature model is given in Table 4-1.

Table 4-1 Overview of the parameters used in the DDWS temperature model

Parameter	Symbol	Value	Unit	Source
Water				
Temperature of influent water	T_w	9	°C	Measured
Thermal conductivity at 15°C	λ_w	0.589	$W \cdot m^{-1} \cdot K^{-1}$	Cengel 2002
Prandtl number at 15°C	Pr_w	8.09	-	Cengel 2002
Heat capacity	c_p	4185	$J \cdot kg^{-1} \cdot K^{-1}$	Cengel 2002
Air				
Ambient temperature	T_∞	14.5-16	°C	Measured
Thermal conductivity at 15°C	λ_a	0.02476	$W \cdot m^{-1} \cdot K^{-1}$	Cengel 2002
Prandtl number at 15°C	Pr_a	0.7323	-	Cengel 2002
Thermal expansion coefficient at 15°C	B	0.00349	K^{-1}	http://www.mhtl.uwaterloo.ca/
Kinematic viscosity at 15°C	N	1.47×10^{-5}	$m^2 \cdot s^{-1}$	Cengel 2002
Pipes				
Thermal conductivity of copper pipes	λ_p	403	$W \cdot m^{-1} \cdot K^{-1}$	Cengel 2002

Statistical analysis

The goodness of fit between measured and modelled values was assessed using the following statistical measures: standard regression (correlation coefficient (R)), dimensionless (Nash-Sutcliffe efficiency (N-S)) and error measurements (root mean square error (RMSE)) (Nash and Sutcliffe 1970, Willmott et al. 1985).

The correlation coefficient indicates the strength of a linear relationship between the model outputs and observed values. The correlation coefficient is derived by dividing the covariance of the two variables by the product of their standard deviations, as given by equation (4-13):

$$R = \frac{\sum_{i=1}^{n}(x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \cdot \sum_{i=1}^{n}(y_i - \bar{y})^2}} \qquad (4\text{-}13)$$

where x_i are the observed and y_i are the modelled values and $\bar{x}$ and $\bar{y}$ refer to the sample mean values.

The value of the correlation coefficient ranges from -1 to +1. If R = 0, there is no linear relationship the simulated and observed values, while if R = 1 or -1, there is a prefect positive or a perfect negative linear relationship between the variables.

The Nash-Sutcliffe efficiency N-S is used to evaluate hydrologic models and to study the ability of a model to reproduce the verification data set (Nash and Sutcliffe 1970). This coefficient is calculated as shown in equation (4-14):

$$N - S = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (4\text{-}14)$$

Nash-Sutcliffe efficiencies are found in the range from -∞ to 1. An efficiency of 1 (N-S = 1) shows a perfect fit between simulated and measured values. An efficiency of lower than zero suggests that the mean value of the measured data would have been a better predictor than the model itself.

As for the error index, root mean square error (RMSE)- which is described as the mean of the squares of errors, is commonly used in model evaluation. This error measurement is valuable because it indicates the extent of error among the simulated and measured values. RMSE is calculated based on equation (4-15):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}} \qquad (4\text{-}15)$$

A RMSE value of 0 indicates a perfect goodness of fit.

Sensitivity analysis

In order to identify the most relevant parameters involved in the DDWS temperature model, a sensitivity analysis was carried out. The sensitivity analysis included a variation of the selected input parameters (given in Table 4-2) by 10% from their initial values. The percentage of the output difference was measured for the data set at the kitchen tap.

Table 4-2 Selected input parameters used in the sensitivity analysis

Parameter	Symbol	Initial value	Unit
Water			
Temperature of influent water	T_w	9	°C
Thermal conductivity	λ_w	0.589	$W \cdot m^{-1} \cdot K^{-1}$
Prandtl number	Pr_w	8.09	-
Heat capacity	c_p	4185	$J \cdot kg^{-1} \cdot K^{-1}$
Air			
Ambient temperature	T_∞	14.5	°C
Thermal conductivity	λ_a	0.02476	$W \cdot m^{-1} \cdot K^{-1}$
Prandtl number	Pr_a	0.7323	-
Thermal expansion coefficient	Β	0.00349	K^{-1}
Pipes			
Thermal conductivity of copper pipes	λ_p	403	$W \cdot m^{-1} \cdot K^{-1}$

4.3 Results and discussion

A graphical visualisation of the simulated and measured values can give a first valuable feedback whether the model outcomes are realistic. Figure 4-6 depicts measured flows and temperature profiles for the kitchen tap in the experimental rig.

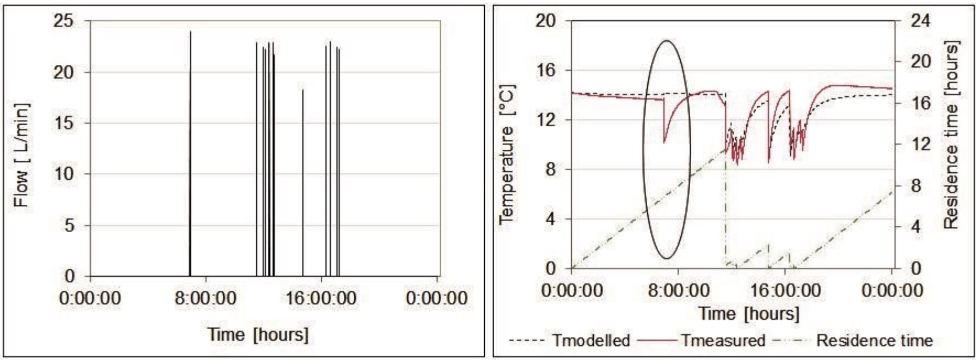

Figure 4-6 Left: Flow measured at the kitchen tap. Right: Modelled and measured temperature profiles at the kitchen tap plus modelled water residence time in the system

As can be seen from Figure 4-6, the dynamics of the measured temperatures are predicted well by the temperature model for DDWSs. However, some irregularities were spotted, i.e. where no temperature drop was predicted by the model, but was measured in the rig (see the ellipse in the Figure 4-6). No change in the residence time was also observed at the same interval, which indicates that EPANET didn't recognize the measured extraction of water at the kitchen tap around 07:30 in the morning.

The explanation for this phenomenon is that the hydraulic network solver EPANET was primarily designed to predict the hydraulics within a drinking water distribution system (Rossman 2000). Drinking water distribution systems consist of pipes with larger diameters, longer pipe sections and higher water flows compared to a DDWS. In the hydraulic models of DDWSs, apart from small diameters (13 mm), the lengths between the junctions and the tap points are as small as ~1 m;. Thus, the mathematical engine most likely starts losing the power to converge accurately with flows over a single time step (10 s), resulting in non-recognition of the real water consumption. To overcome this drawback, an attempt was made to tune the flow input.

The tuning of the input flow included the process of determining best estimates for unknown flows by comparing model outcomes and measured temperature record. Wherever the irregularities between modelled and measured temperatures were found, the measured input demand patterns were manually modified by:

- assigning 10 -20 s of the additional flow of the same magnitude
- distributing the flow over a shorter time step, i.e. 5 s.

The graphical visualisation of the results and the cumulative probability curves that were generated before and after tuning the input flow are presented in Figure 4-7.

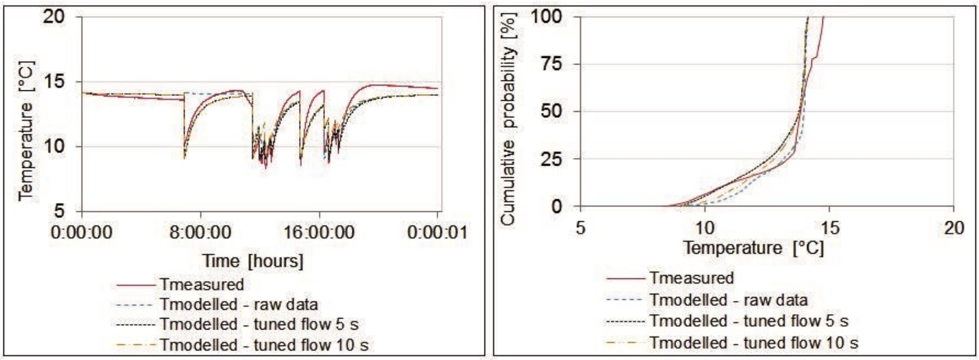

Figure 4-7 Water temperature profiles and cumulative probability curves for observed and simulated data at the kitchen cold tap

As it is evident from Figure 4-7, both addition of supplementary flows of 10 to 20 s (Tmodelled - tuned flow 10 s in Figure 4-7) and distributing the flow over 5 s (Tmodelled - tuned flow 5 s in Figure 4-7) result in more adequate trends of the temperature profiles. This implies that better hydraulic performance in EPANET 2.0 was accomplished with the aid of the flow adjusting procedure.

The ability of the temperature model to reproduce the temperature dynamics in DDWSs was assessed by statistical measures, applying the raw and tuned flow input, shown in Table 4-3.

Table 4-3 Statistical measures for temperature model performance – cold water line

Flow input	R	N-S	RMS
Raw data – time step 10s	0.822	0.662	0.867
Tuned flow input – time step 10 s	0.899	0.783	0.695
Tuned flow input – time step 5 s	0.923	0.809	0.651

Table 4-3 shows that tuning the flow input improved model performance in terms of all three statistical measures. The values of both correlation coefficient - R and Nash-Sutcliffe efficiency N-S increased (from 0.822 to 0.923 and from 0.662 to 0.809, respectively) while the error index, RMSE, decreased from 0.867 to 0.651. In general, model prediction can be judged as “very good” if N-S > 0.70 and R>0.90, as for the error indices that are represented in the units of the temperature (ºC or K), error values close to zero indicate perfect fit. RMSE can be judged as low if RMSE is smaller than one-half the standard deviation of measured time series (Singh et al. 2004). In our case, the standard deviation value was 1.49, implying that the error index may be considered low for models with tuned flow.

We need to mention that discrepancies between measured and modelled results were observed in the hours with no flow. This was expected, as the ambient temperature fluctuates by a few degrees on a daily basis, while the model assumes constant ambient temperature. The discrepancies also had an effect on the statistical parameters. If the data during the daytime with no flow are excluded from the statistical analysis (from 00:00 to 6:00 and from 19:00 to 00:00), R and N-S were improved to 0.937 and 0.992, respectively, while RMSE was of the same order, 0.704.

Validation was done for hot water lines for the extended DDWS (Figure 4-3) and visualisation graph and cumulative probability curve of temperature at the hot bathroom tap is given in Figure 4-8. Because the demands of the hot bathroom tap were long enough (> 20 s), the pattern was not tuned by assigning extra flows. However, an additional simulation was done with 5 s time step, to assess the difference in temperature profiles if shorter time steps are applied.

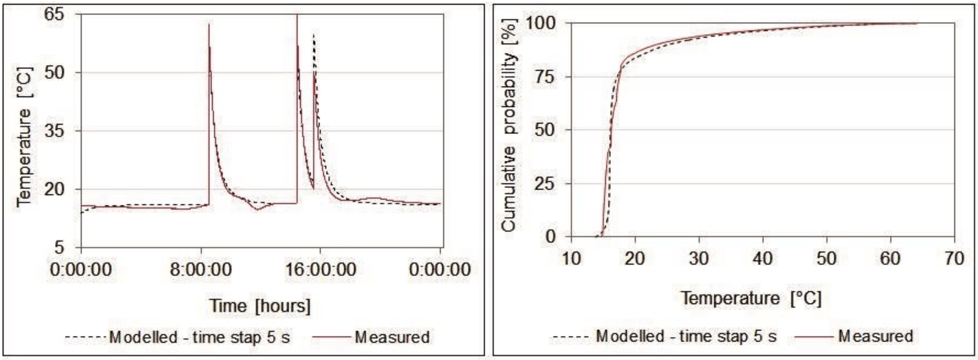

Figure 4-8 Water temperature profiles and cumulative probability curves for observed and simulated data at the bathroom sink hot water tap in extended DDWS

Graphical comparison, presented in Figure 4-8, shows that the model is able to reproduce temperature profiles at the hot water taps, as well. In Table 3, the statistical measures are summarized.

Table 4-4 Statistical measures for model performance – hot water line for extended DDWS

Flow input	R	N-S	RMS
Raw data – time step 10s	0.980	0.882	2.227
Tuned flow input – time step 5 s	0.983	0.954	1.452

The simulation with shorter time step (5 s) yielded better statistical parameters, whereas RMSE and N-S were improved from 2.227 to 1.452 and from 0.882 to 0.954, respectively, while correlation coefficient was in the same order, 0.980 and 0.983, respectively. Here again, excluding the hours without the demand from the statistical analysis (from 00:00 to 6:00 and from 19:00 to 00:00), resulted in improved R, N-S, RMSE values to 0.996, 0.981, and 0.838, respectively). Even though the statistical measures for the temperature modelling when employing tuned hydraulic models are satisfactory, one must bear in mind that it is of high importance to have a model with limited errors in terms of hydraulics. Thus, to obtain representative results when having single step demands, it is necessary to assess whether or not EPANET recognized the flow, which can be done by analysing the extent of residence time at a given flow.

The measured and modelled data revealed that the water temperature dynamics in homes is mainly driven by the water consumption pattern, and is limitedly dependent on the size and layout of the DDWSs. Both modelled and measured data (measured data are given in Figure 4-9) showed that drinking water is being warmed up by 0.5 to 2°C within the copper DDWSs, namely from the inlet point to the tap in use, depending on how far from the inlet point the demand takes place. Therefore, if the drinking water temperature is determined by sensors in drinking water distribution networks, the temperatures at the points of use can be underestimated.

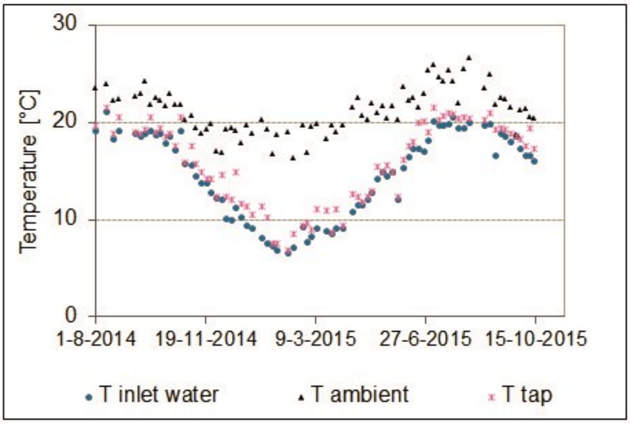

Figure 4-9 Overview of the measured ambient temperature, temperature of inlet drinking water and temperature at the shower tap

The sensitivity analysis was carried out to measure the influence of the input parameters on the model performance.

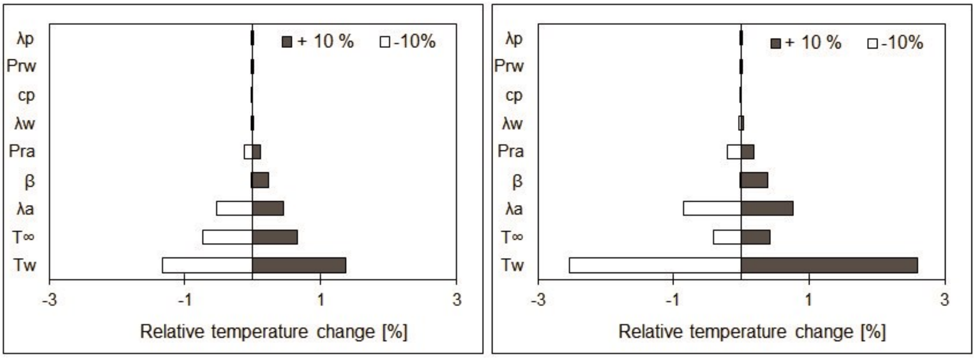

Figure 4-10 Sensitivity of the water temperature model to the input parameters. Left Model outputs for all day simulation. Right Model outputs during extraction hours (from 06.00 - 19:00)

The sensitivity analysis (Figure 4-10 left) for all day simulation data revealed that the most relevant parameters are the temperature of inlet water (T_w), the temperature of air (T_∞) and the thermal conductivity of air (λ_a). If only extraction hours are included in the sensitivity analysis (Figure 4-10 right), the inlet water temperature was found to play a more important role, as variation of ±10% in the input temperature leads to ±2.5% of relative change in the output temperature. Here again, the most sensitive parameters were found to be the temperature of inlet water, the temperature of air and the thermal conductivity of air, and, hence, these values need to be put in the model with high accuracy. From the sensitivity analysis it can be concluded that, when modelling water temperature in DDWSs, the most important transfer process is the exchange process of heat between water and air through the pipe wall. Due to the fact that water flows, driven by water demand patterns, were observed to have a crucial impact on the model prediction accuracy, calibration of the sensitive parameters was not performed in the current research.

In the conducted research, DDWSs made of copper were used for the model validation. Because the model is based on fundamental thermodynamic principles, it can be used for other DDWSs pipe materials as well. Nevertheless, the applicability of the model for other pipe materials that are commonly applied in DDWSs needs to be experimentally validated. If the temperature model shows the same accuracy for the other pipe materials, it would be possible to couple the temperature model for DDWSs with a model that predicts the temperature of the water in the drinking water distribution system, with the goal to model the temperature dynamics from the treatment facilities (reservoirs) to the points of actual water use (drinking water taps in DDWSs).

4.4 CONCLUSION

A temperature model for DDWSs was developed, by integration of a temperature model, a hydraulic model and a demand pattern model (SIMDEUM). A combination of graphical and statistical techniques was used for model evaluation. A statistical analysis showed that the model is able to adequately predict the temperature profiles within DDWSs. The most sensitive parameters in the model are the temperature of the inlet water, the temperature of air and the thermal conductivity of air, implying the most dominant transfer process is the (convective) heat exchange between water and air through the pipe wall. Because the model is based on fundamental thermodynamic principles, it is believed that this model can be used for other pipe materials which are used in DDWSs.

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CHAPTER 5

5 INFLUENCE OF WATER STAGNATION AND TEMPERATURE ON THE DRINKING WATER QUALITY IN DDWSS

Abstract

The drinking water quality changes during the transport through the distribution system. Domestic drinking water systems (DDWSs), which include the plumbing between the water meter and consumer taps, are the most critical points in which quality may be affected. In the distribution networks, the drinking water temperature and water residence time are regarded as indicators for water quality. This chapter describes an experimental research on the influence of stagnation time and temperature variation 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 hours of stagnation) were carried out and 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 activity in stagnant water appears to be driven by the temperature of fresh water. Biofilm formed in the shower pipe contained more total and intact cells than kitchen pipe biofilm. Alphaproteobacteria were found to dominate in shower biofilm (78% of all Proteobacteria), while in the kitchen tap biofilm Alphaproteobacteria, *Betaproteobacteria* and *Gammaproteobacteria* were evenly distributed.

Keywords: *drinking water, water quality, water temperature, water stagnation*

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5.1 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 the application of biostable materials (Van der Kooij 2000, 2003); 5) optimization and maintenance of distribution networks (self-cleaning networks and regular flushing of networks) (Vreeburg 2007, Vreeburg and Boxall 2007); 6) the statuary monitoring of produced and delivered drinking water. All these approaches combined have resulted in a low average frequency of interruptions affecting customers (on average 7.5 minutes per connection per year) (Van der Kooij and van der Wielen 2013), 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, whereas over 95% of the Dutch population consumes tap water (de Moel et al. 2006a, Smeets et al. 2009a). However, given the complexity of processes occurring within the water transport and 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, Van der Kooij 2000, Van der Kooij and van der Wielen 2013, Vreeburg 2007, Vreeburg and Boxall 2007).

The domestic drinking water distribution system (DDWS), being a portion of the distribution system that includes plumbing between the water meter and consumers' taps, is the final stage in a drinking water supply system. DDWSs are characterized by lengthy 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 total 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 the 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 chlorination is not used as a disinfection step and where drinking water is distributed without a persistent disinfectant. As stated before, in The Netherlands 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 re-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 samples from DDWSs than in samples from the distribution networks in The Netherlands (van der Wielen and van der Kooij 2013), which proves the importance of DDWSs in the entire process of safe drinking water supply.

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. In a pilot study that was carried out in Finland, it was reported that a stagnation time of 16 hours in DDWSs can lead to an increase in bacteria counts over one log unit (Lehtola et al. 2007). In addition to this, the overnight stagnation in DDWSs was found to stimulate microbial activity and richness (Lautenschlager et al. 2010, Prest et al. 2013).

The drinking water temperature is another factor to consider when assessing water quality, as it is known to affect the chemical and microbiological processes within the distribution phase (Boulay and Edwards 2001, LeChevallier et al. 1996b, LeChevallier et al. 1996c, Li and Sun 2001, Sarver 2010, Singh and Mavinic 1991, Uhl and Schaule 2004, Van der Kooij 2003). In The Netherlands, water temperature in the distribution networks varies from a few degrees Celsius in the winter months to about 20°C in the summer months (Van der Kooij and van der Wielen 2013b). Once the drinking water is delivered to a DDWSs, thermal equilibrium between stagnant water and surrounding air/walls takes place. For instance, as indicated by a temperature model and confirmed by measurements in the present research, the rate at which the drinking water is being warmed up to the room temperature is ~0.1°C per minute. According to 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 network could even be about 20°C during the winter season, which may result in increase in biological activity in DDWSs (Van der Kooij 2003).

Even though the water temperature and water residence time are regarded as indicators for water quality in distribution networks, little is known about their influence on water quality in DDWSs. In order to evaluate the influence of the stagnation time (i.e. up to 168 hours of stagnation) and temperature effect on chemical and microbial quality in more detail, two sets of stagnation experiments (winter and summer) were performed in a full scale copper DDWS. To study the influence of fresh water temperature on microbial activity in stagnant water, long term experiments with stagnation time of 10 hours (overnight stagnation) were carried out over a study period of nine 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.

5.2 MATERIALS AND METHODS

5.2.1 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 (Figure 4-2, and Figure 4-4)

The design of the experimental plumbing rigs was done according to a plan of a 2 floor house (Typical Dutch House). Inside a Typical Dutch house, there are three locations where plumbing pipes go: kitchen, bathrooms/toilets, and laundry/water heater room, with in total 11 plumbing fixtures. On the first floor of the house a kitchen (with hot-cold taps and a dishwasher) and a guest toilet (with a toilet bowl and a washbasin) are located. On the second floor a family bathroom (with a toilet bowl, shower and a sink) is placed, while at the third floor a washing machine and a hot water boiler are present.

Configuration of the experimental rig complies with the Dutch home plumbing codes NEN 1006 (NEN1006 2002). The DDWS, which was used for stagnation experiments, consists of 2 vertical lines and 4 horizontal branches of copper (manufactured in accordance with European Standard EN 1057), namely vertical copper composite of 22 mm diameter - carrying cold water to the upper floors, vertical copper tube of 15 mm (ID) –delivering hot water from a 50 L water heater and copper tubing's of 15 mm-supplying cold and hot water from the vertical lines to the 11 plumbing fixtures (solenoid valves), as given in Figure 4-4 The total length of the pipes is 48.6 m and the volume of the plumbing rig is 6 L.

In order to be able to mimic a realistic drinking water consumption at the household level, the test rigs comprise 11 solenoid valves (point of use) per system. The valves were configured to run automatically (on and off mode) according to the one year demand patterns (time step of 10 seconds) generated by SIMDEUM model (**SIM**ulation of water **D**emand, an **E**nd **U**se **M**odel). SIMDEUM model, developed by KWR Watercycle Research Institute (Nieuwegein, The Netherlands), is a stochastic model which is grounded on statistical information of water appliances and water consumers. SIMDEUM generates water demand patterns based on consumers' behaviour, taking into consideration variabilities in DDWSs and water-using appliances (Blokker et al. 2010, Blokker et al. 2006). In this research, the SIMDEUM demand patterns of two-person household were used.

Results from a study that was done in Finland (Lehtola et al. 2004) revealed that copper had an effect on HPC counts and biofilm composition only in the first 200 days, and thus in this research a stabilization period of 210 days was considered before the experimental start-up. During the stabilization period, every tap in the experimental rig was flushed twice a day for 5 min at least 4 times a week.

5.2.2 Stagnation experiments

Before every stagnation experiment, water was flushed through the system by opening the solenoid valves for 5 minutes, at a flow rate between 20 - 30 L/min. After flushing the pipes samples of fresh water were collected at the inlet point, cold kitchen tap and cold shower tap. The water at the inlet (connection) point was sampled to assess the difference, if any, in fresh water quality between the inlet (connection) point and the points of use in the DDWSs, because the length of the pipe that delivers water from the connection point to the lab rigs was 40 m. After collecting the fresh water samples, water was allowed to stagnate in the drinking water plumbing rig system for 40 min, 4 hours, 10 hours, 24 hours, 48 hours, 96 hours and 168 hours. After every stagnation interval water samples (i.e. stagnant water) were taken at 2 sampling taps: kitchen tap and shower tap. To study the influence of different stagnation times on water quality parameters, the entire volume of stagnant water was collected (1.05 l for the kitchen tap and 0.7 L for the shower tap). Stagnant water samples were collected into a sterile bottle and then transferred into the sampling cups for further analysis. Samples were stored on ice in a cooler for maximum 12 hours until analysis at Het Waterlaboratorium in Haarlem, The Netherlands.

To examine the influence of fresh water temperature on the quality of the drinking water that is left for overnight stagnation of 10 hours, long term experiments were carried out, using the previously described approach. Sampling campaigns for fresh and 10 hours stagnant water were done every two weeks, for the study period of 8 months.

5.2.3 Water and biofilm analysis

After 8 months of the stagnation experiments, systems were run for additional 6 months (total 430 days after the experimental start-up). After that period kitchen and shower pipes (3 times 20 cm long pipe specimens) were cut from the experimental rigs. The pipe specimens were filled with sterilized water and were closed by autoclaved silicone rubber stoppers and were sealed with ethanol - treated parafilm. Biofilms were detached by three consequent two minutes cycles of low energy ultrasonic treatments (Bath sonicator device, Branson 2510), before further analysis (Magic-Knezev and van der Kooij 2004). The biofilm results were normalized with respect to the surface area of the pipes (cm^2) and measured volume (mL).

After acidification with hydrochloric acid, the concentrations of copper and zinc in fresh and stagnant water were determined by Inductively Coupled Plasma mass spectrometry (ICP-MS). The detection limit of this method was 0.1 μg/L.

The content of total organic carbon (TOC) in water samples was determined in triplicates applying the combustion catalytic oxidation/NDIR method (TOC-V CPH, Shimadzu, Duisburg, Germany), which is based to the Dutch standard procedure NEN-EN-1484 (NEN 1997a), with the detection limit of 10 μg/L and the standard deviation of ±10%.

The number of culturable bacteria in water and biofilm samples was determined by the heterotrophic plate count (HPC) method which was performed following the Dutch guidelines for drinking water NEN-EN-ISO 6222 (NEN 1999).

The process of staining for total and intact cell counts and flow cytometry (FCM) was done for water and bacterial suspensions obtained from the biofilm samples according to the protocol described previously (Hammes et al. 2008, Hammes et al. 2011, Nakamoto et al. 2014, Vital et al. 2012).

Total ATP concentration in water and biofilm samples was measured by employing the reagent kit for bacterial ATP (Celsis; Brussels, Belgium) and a luminometer (Celsis Advance^{TM}, Celsis, Netherlands) according to the protocol described in a study (Magic-Knezev and van der Kooij 2004). The detection limit of this ATP method was 1 ŋg/L.

The cultivation-independent investigation of microbial diversity and richness of water and biofilm was done by next generation sequencing at KWR in Nieuwegein, The Netherlands. Collected samples (250 mL of fresh water sample and 30-45 mL of suspensions obtain by sonication of biofilm samples) were filtered through polycarbonate membrane filters with a pore size of 0.2 µm to concentrate bacterial cells. The bacterial cells were lysed by a combination of lysis buffer and bead-beating This was done after folding the filter and putting the folded filter in a bead tube containing BF1 and BF2 buffers of the Power Biofilm Kit (MoBio, Carlsbad, USA) lysis buffer. DNA was purified as described in the Power Biofilm protocol provided by MoBio. The V3-V4 region of the bacterial 16S rRNA genes were PCR-amplified and processed. Paired-end sequences were generated on the Illumina MiSeq system using the 2X 300 cycles protocol and paired end sequences were merged, using FLASH (Magoč and Salzberg 2011) and all subsequent analyses were performed using the version 7.5 of the Bionumerics software (Applied Maths, Sint-Martens-Latem, Belgium). Quality filtering was based on PHRED scores by excluding sequence reads with a minimal score of 20 and excluding reads with an average quality below 30. The final sequences were identified against the Silva taxonomic database (Pruesse et al. 2007, Yilmaz et al. 2014).

5.2.4 Statistical analysis

Statistical analysis was carried out to determine if the measured data sets (copper, zinc, HPC, TCC and ATP values) from fresh water at three the different taps (inlet, kitchen and shower)were significantly different. The data that were found to be normally distributed were tested by the t test, while in case of the non-normal distributed nonparametric tests (Kruskal-Wallis tests) were performed (Kruskal and Wallis 1952).

The statistical analysis was done using the Minitab 17 statistical software (Minitab 2014). In this study, differences were considered to be significant if the p-value was less than 0.05.

In order to visually summarize and compare fresh and stagnant water quality parameters for conventional and extended systems, data were plotted according to the box plot methodology. Box plot displays the mean, quartiles, minimum and maximum observations, and outliers for a group of investigated parameters (Tukey 1977).

5.3 RESULTS AND DISCUSSION

5.3.1 Fresh water

According to Kruskal-Wallis test statistically insignificant difference ($p > 0.05$) was found between the fresh water samples coming from the inlet tap, kitchen tap and shower tap for all examined parameters. The quality parameters of the fresh water delivered to the study site during the winter and summer experiments are presented in Figure 5-1. The temperature of fresh water samples was 6-8°C during the winter experiments and 21.5-23°C during the summer experiments. Ambient temperature around the DDWS was measured to be 16-20.5°C during the winter experiments and 19.5-26°C during the summer experiments.

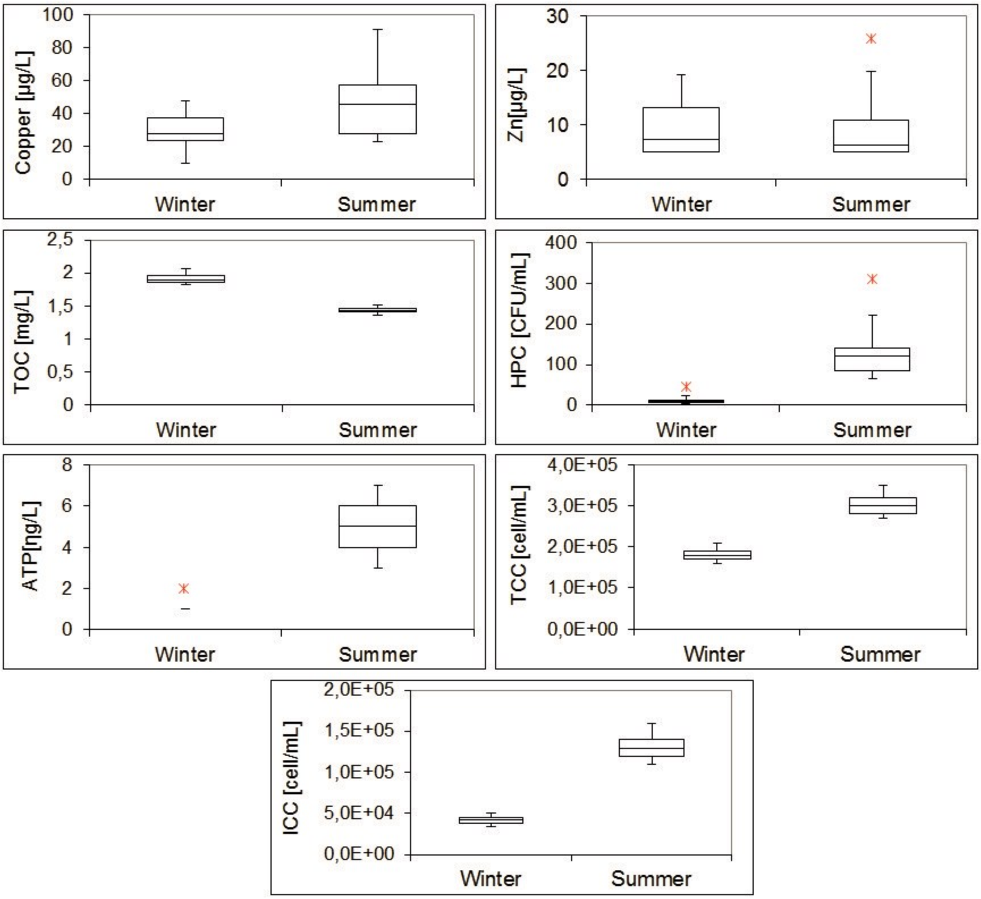

*Figure 5-1 Box-plots of water quality parameters (Cu, Zn, TOC, HPC, ATP, TCC, ICC) for fresh drinking water samples (inlet, kitchen and shower taps), during winter and summer experiments (n = 21), * - maximum outlier.*

The copper concentrations in fresh water samples (Figure 5-1) were, on average 30 µg/L (range 10 – 50 µg/L) in winter experiments and 50 µg/l (range 20-90 µg/L) in summer experiments, respectively. As water passes through copper pipes before the inlet point, the discrepancy of 20 µg/L in copper levels between winter and summer samples, could be related to the leaching of copper under higher temperatures from the copper pipes before the experimental rig. The World Health Organization (WHO) recommends 2 mg/L as a maximum concentration value for drinking water (WHO 2004). The measured copper levels in fresh water samples during both winter and summer were found to be below the guideline value proposed by WHO and therefore they could pose a negligible risk to human health.

As shown in Figure 5-1, the average measured levels of zinc in fresh water samples were found to be around 7 µg/L, during both winter and summer experiments. Brass (alloy of copper and zinc) components are widely applied in drinking water distribution systems as valves, faucets and other fixings. Even though there is no health-based guideline value for zinc in drinking water, at zinc concentrations above 3 mg/L an undesired colour and taste can develop (WHO 2003). In this research, the measured zinc concentrations in fresh water samples were far below the proposed aesthetic guideline.

The total organic carbon (TOC) is one of the most commonly applied measures to indicate the natural organic matter (NOM) concentration present in a water sample. The content of total organic carbon in the fresh samples was, on average 1.89 mg/L (range 1.83 – 2.06 mg/L) in the winter experiments and 1.43 mg/L (range 1.37 – 1.52 mg/L) in the summer experiments, respectively, which is in line with seasonal variation of TOC content in treated water, presented in a recent research (Prest 2015).

The general hygienic quality of drinking water is generally monitored with HPC analysis. In The Netherlands, the official guideline is 100 colony forming units per mL (CFU/mL) in the distribution network.

As can be seen in Figure 5-1, measured HPC was considerably lower during the winter experiments, average 10 CFU/mL, when compared to the average measured values of HPC during the summer experiments of 130 CFU/mL. Elevated HPC during summer experiments may be linked to the higher drinking water temperature, which can cause re-growth of heterotrophic bacteria in the distribution network.

Adenosine tri-phosphate (ATP) represents the main energy carrier molecule and is detectable and measurable in all living cells. According to Van der Kooij (2003), ATP concentrations over 10 ng/L are considered relatively high in drinking water distributed without persistent disinfectant, while ATP concentrations below 1 ng/L are considered low. As shown in Figure 5-1, microbial activity during winter (ATP~1 ng/L) can be considered low. In summer, however, the ATP concentrations of the fresh water samples were somewhat elevated (average ~5 ng/L) and could be related to higher microbial activity. This is in line with findings of previous research, in which was reported that the ATP concentration in the distributed water was significantly lower in the winter than in the summer and autumn, suggesting that lower water temperatures maintained limited microbial activity in the distributed drinking water (van der Wielen and Van der Kooij 2010).

The total number of cells in fresh water samples for winter and summer experiments was in the range from 1.6x10^5 cell/mL to 2.15x10^5 cell/mL and from 2.7x10^5 to 3.5x10^5 cell/mL, respectively, which falls within the range of TCC in unchlorinated drinking water samples (Hammes et al. 2010, Liu et al. 2013). The TCC was significantly higher during summer experiments, which can be attributed to the influence of elevated water temperature on microbial activity and re-growth in distribution networks, which corresponds well with previously discussed results on HPC and ATP measurements. Though water is supplied without residual disinfectant in the Netherlands, it was found that ~25% of total cells in fresh water were alive/intact in winter experiments and ~45% of total cells in were alive/intact in summer experiments. In addition to this, the percentage of the intact cells with high nucleic acid content (ICC-HNA) of the total intact cells during winter and summer experiments was ~33% and ~56%, respectively. This increase might be another evidence of the bacterial re-growth in the distribution network under higher water temperatures, as the HNA-subgroup is responsible for the most important part of the bulk activity.

5.3.2 Stagnant water

In Figure 5-2 measured copper concentrations during the winter and summer stagnation experiments are summarized.

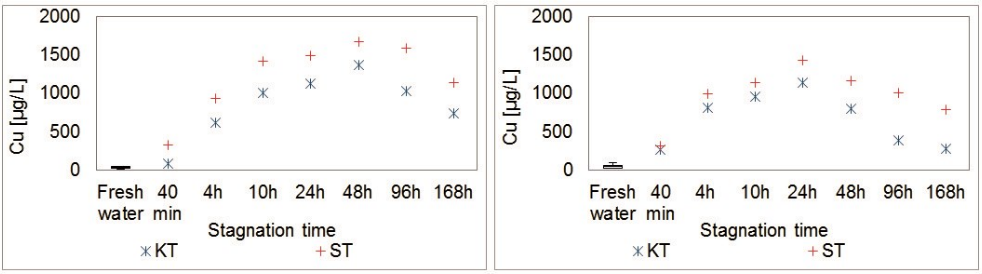

Figure 5-2 Copper concentrations in water samples during winter (left) and summer (right) stagnation experiments. KT - kitchen tap; ST – shower tap. Fresh water: inlet, kitchen and shower.

Concentrations of copper in water samples increased with the stagnation time in both winter and summer experiments (Figure 5-2). Maximum copper levels of 1370 µg/L in a water sample from the kitchen tap and 1680 µg/L in a water sample from the shower tap were assayed after the 48 h of stagnation in winter experiments. Maximum copper levels of 1140 µg/L in a water sample from the kitchen tap and 1470 µg/L in a water sample from the shower tap were reached after the 24 h of stagnation in summer experiments. The difference in copper levels (of ~300 µg/L) between the samples from the kitchen and shower tap might be a result of the microclimate around the experimental DDWS, as the ambient temperature is higher on higher floors, i.e. the ambient temperature on the 1st floor (where the shower tap is located) was 1.1 ± 0.3 C higher than the ambient temperature on ground floor (where the kitchen tap is placed). The microclimate in real systems, however, is different and is dependent on the human thermal comfort in the built environment (Rupp et al. 2015).

The profile of copper leaching was found to be different between two sets of experiments, i.e. the peak copper concentration was reached after 48 h in winter experiments and after 24 h in summer experiments. As explained in (Edwards and Sprague 2001), under oxic conditions copper metal surface corrodes creating a scale layer which equilibrates with the water, controlling the concentration of free-copper. It is common knowledge that the solubility of oxygen decreases as water temperature increase, which might explain the peaking time difference, as more oxygen can be available for reaction with the metal surface during winter experiments. Furthermore, a reaction between free copper and organic matter in solution may happen, and the products of the reaction may be soluble compounds, particulate compounds and precipitates. These reactions lead to increased concentrations of copper corrosion by-products, maintaining higher free-copper concentrations in water than in cases where NOM is not present. As given before, TOC levels were found to be higher in winter experiments, which might explain the shift in the copper peaking during the winter experiments. Also, a study of (Rushing and Edwards 2004) revealed that mechanical stresses could develop within pipes as a result of temperature changes. Mechanical stress within pipes might result in disturbance of the scale, loss of the protection layer and copper release to the drinking water. Changes in temperature, as during the winter experiments when the water temperature changes from 6°C to 20.5°C in DDWSs, might induce the mechanical stress which in turn may lead to higher release of copper (up to 300 µg/L) during the winter experiments. In both experimental sets, after reaching the maximum concentrations copper concentrations in stagnant water were found to decrease. This phenomenon was explained by the depletion of dissolved oxygen and subsequent precipitation of dissolved cupric ions as cuprous oxide after reacting with metallic copper (Lytle and Schock 2000).

Levels of zinc concentrations during stagnation experiments are summarized in Figure 5-3.

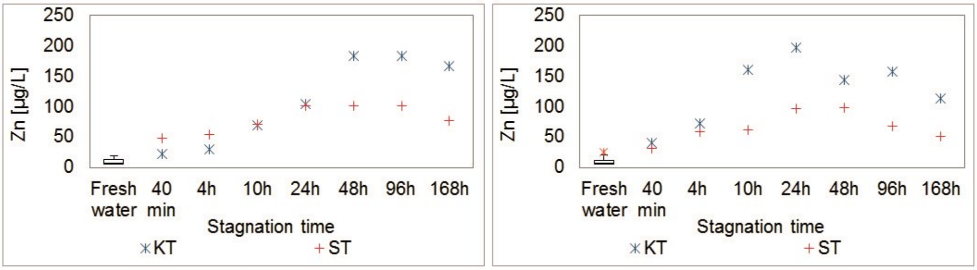

Figure 5-3 Zinc concentrations in water samples during winter (left) and summer (right) stagnation experiments. KT - kitchen tap; ST – shower tap. Fresh water: inlet, kitchen and shower.

Similar to the previous discussion about copper leaching in stagnation experiments, concentrations of zinc in water samples increased with the stagnation time in both winter and summer experiments (Figure 5-3). Maximum zinc concentrations of 180 µg/L in a water sample from the kitchen tap and 100 µg/L in a water sample from the shower tap were reached after the 48 h of stagnation in winter experiments. Maximum zinc concentrations of 200 µg/L in a water sample from the kitchen tap and 100 µg/L in a water sample from the shower tap were measured after the 24 h of stagnation in summer experiments. The difference in released zinc (of µg/L) between the samples from the kitchen and shower tap might also be due to the microclimate conditions around the set-up. After peaking, drop in zinc concentrations was observed with increase in stagnation time. As previously reported that NOM has negligible effect on leaching of zinc from brass elements (Korshin et al. 2000), the decrease in zinc concentrations can be related to the drop in dissolved oxygen levels in stagnant water, as oxygen is the limiting parameter in the zinc leaching process (Turner 1962), after which the precipitation of the corrosion product (meringue) on pipe surface may happen (Zhang 2009).

The distribution of TOC concentration over the stagnation time is presented in Figure 5-4.

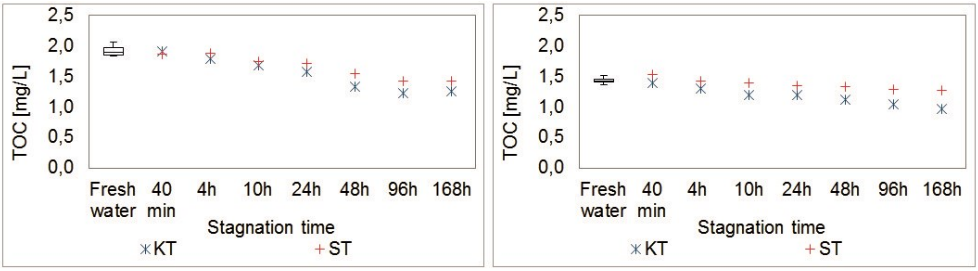

Figure 5-4 TOC concentrations in water samples during winter (left) and summer (right) stagnation experiments. KT - kitchen tap; ST – shower tap. Fresh water: inlet, kitchen and shower.

As is evident from Figure 5-4, TOC concentrations generally decrease with the stagnation time in both sets of experiments (winter and summer), whereas the maximum decrease was found after 168 h of stagnation. The maximum decrease of 30% in TOC content was detected in water samples in the winter experiments, while the maximum drop in TOC levels was estimated to be 15% of the average TOC in fresh water samples in the summer experiments. The decrease in TOC could be attributed to both microbial activity in water and biofilms formed along the pipelines and adsorption of the organic matter onto pipe surfaces. Another finding is that regardless of the initial TOC concentrations, the "final" concentrations, i.e. the ones after 168 hours of stagnations, are similar. This might imply that in summer a portion of TOC is consumed in the distribution networks, while in winter the TOC is mainly consumed in DDWSs. Therefore, it can be concluded that TOC consumption happens either in distribution networks, or in DDWSs, but only if optimum temperatures are reached.

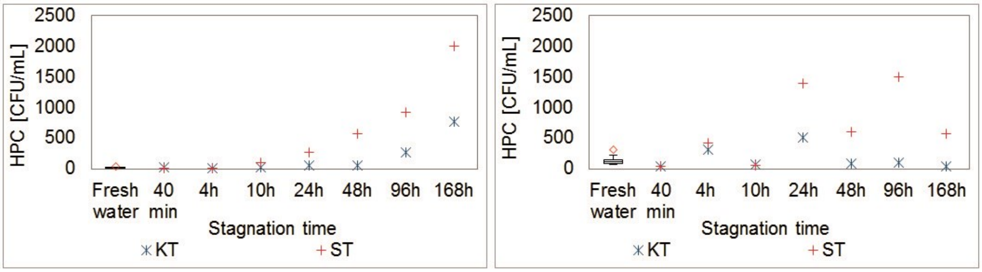

Figure 5-5 HPC levels in water samples during winter (left) and summer (right) stagnation experiments. KT - kitchen tap; ST – shower tap. Fresh water: inlet, kitchen and shower.

During the winter experiments the numbers of heterotrophic bacteria increased exponentially with stagnation time, for both kitchen and shower tap (Figure 5-5). The stagnation time of 168 h resulted in 100 and 200-fold increase in the HPC levels for drinking water from kitchen and shower tap, respectively, compared to the HPC levels after 40 min of stagnation in the winter experiments. In the distribution systems, the growth of HPC bacteria depends on factors as temperature, disinfectant residual, nutrient concentrations, corrosion control and pipe material (LeChevallier et al. 1996, Volk et al. 2000). This may indicate that, though the nutrients might be available, the HPC bacteria didn't have favourable conditions, in terms of required temperature, to grow in unchlorinated drinking water distribution systems in the winter months. However, in the test rig of DDWS, where the ambient temperature (the temperature of the stagnant water) is almost 15°C higher than in the distribution systems during the winter months, those favourable conditions might be reached, resulting in the exponential increase of HPC levels with stagnation time. Data from the summer experiments show that despite the fact the number of HPC increases in some cases with stagnation time, no consistent pattern to these increases was observed. Even though the data were found to be too scattered to be conclusive, a possible reason for this this trend could be biofilm detachment under oligotrophic conditions of stagnant water (Hunt et al. 2004, Lautenschlager et al. 2010).

Furthermore it was observed that after 24 hours of stagnation, higher HPC levels were measured in water samples from the shower tap than in the samples from the kitchen tap, for both sets of experiments. Looking at the experimental rig, water is delivered to the kitchen tap through the pipe that is also supplying water to the dishwasher tap, while shower tap and bathroom tap are connected to the same pipe. According to

SIMDEUM consumption patterns used in this study, water is being more frequently used at the kitchen/dishwasher taps than at the bathroom/shower taps. Longer stagnation in the pipe that supplies water to the shower and bathroom tap might lead to the growth of richer biofilm, in terms of culturable bacteria, which could result in a higher HPC levels in shower samples after 24h of stagnation, when compared to the kitchen samples.

Figure 5-6 shows ATP profiles for winter and summer stagnation experiments.

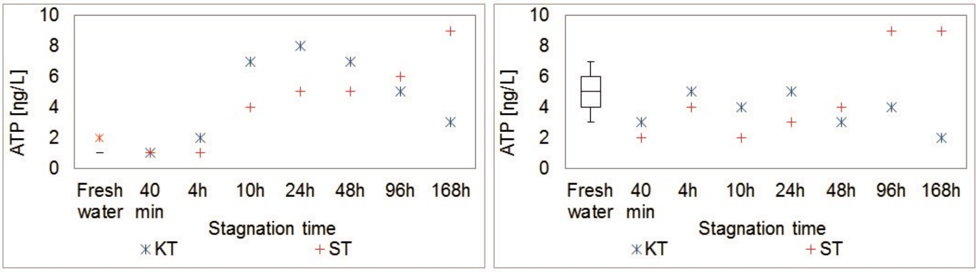

Figure 5-6 ATP concentrations in water samples during winter (left) and summer (right) stagnation experiments. KT - kitchen tap; ST – shower tap. Fresh water: inlet, kitchen and shower.

The results demonstrate a 4-8-fold increase in ATP content of water samples after 10 and 24 hours of stagnation in the winter experiments for both kitchen and shower taps. The increase in ATP content might indicate that stagnation of water can promote microbial activity. This observation is consistent with the findings from previous research of induced microbial activity after overnight stagnation of water in DDWSs (Lautenschlager et al. 2010). After water stagnation of 48 hours, however, different patterns in ATP concentrations were observed in water samples from the two considered taps. For the water sample from the kitchen tap, a reduction in ATP after 48 hours of stagnation was observed, while for the shower sample ATP content continued to increase. The ATP profile for the summer experiments shows that no increase in microbial activity was measured (except for the shower water samples after 96 hours of stagnation). A sudden 2-fold increase in ATP concentration was measured after 96 and 168 hours of stagnation time in the samples from the shower tap.

In Figure 5-7, the influence of stagnation time on intact bacterial cell concentrations is presented.

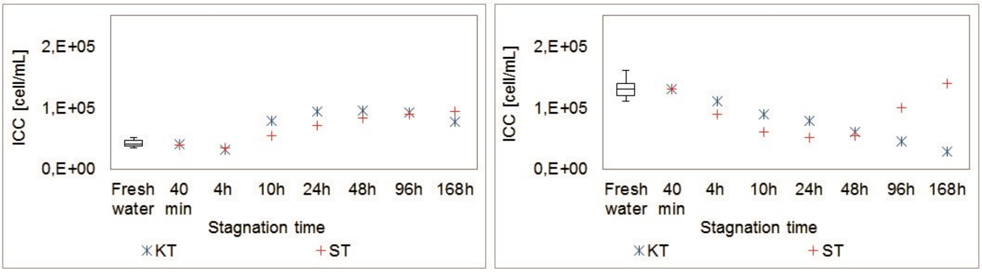

Figure 5-7 ICC levels in water samples during winter (left) and summer (right) stagnation experiments. KT - kitchen tap; ST – shower tap. Fresh water: inlet, kitchen and shower.

During the winter experiments stagnation promoted microbial re-growth, as on average 2-fold increase in intact cell concentration after 10 hours of stagnation, which corresponds well with the results from previous research (Lautenschlager et al. 2010, Lehtola et al. 2007). The increase in the intact cell numbers was not as pronounced as for HPC levels (Figure 5-5). This might imply that the bacteria growing in DDWSs are highly culturable (Lehtola et al. 2007). In the summer experiments, stagnation resulted in linear reduction in intact cell counts for the kitchen, i.e. 5-fold reduction after 168 hours was measured. For the shower tap, initially a steady decrease in ICC was observed, i.e. a 3-fold reduction in intact cell numbers was found after 48 hours of stagnation. After 96 and 168 hours, elevated intact cell concentrations were measured compared to the results of 48 hours of stagnation, which was also observed in ATP measurements (Figure 5-6), which might be due to be biofilm detachment under oligotrophic conditions of stagnant water (Hunt et al. 2004, Lautenschlager et al. 2010). The HNA footprint of all stagnant water samples didn't considerably change during the summer stagnation experiments (~50% ICC-HNA bacteria of ICC), while during the winter experiments a linear increase of up to 2.5-fold was measured in HNA-ICC cells in stagnant samples, which indicates that higher temperature in the DDWS coupled with the stagnation of water promoted microbial regrowth during the winter experiments.

5.3.3 Influence of water temperature and overnight stagnation on microbial properties of drinking water – long term experiments

In Figure 5-8, change in growth patterns, expressed by FCM, ATP and HPC measurements, is given.

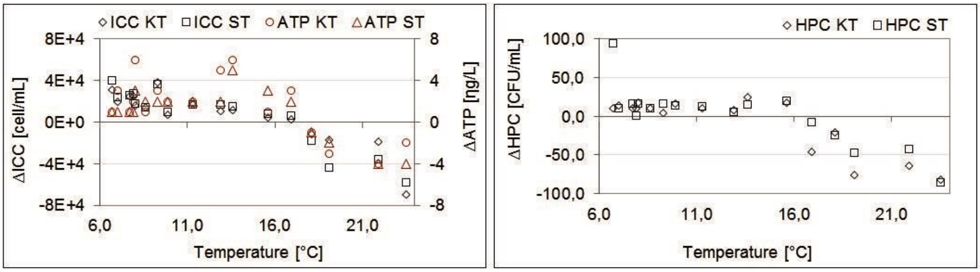

Figure 5-8 Change in microbiological parameters during overnight stagnation in long term experiments. Left: Change in ICC and ATP concentrations. Down: Change in HPC levels. KT- kitchen tap, ST: shower tap.

Over the experimental period, the temperatures of fresh water ranged from 6°C to 23°C, and the temperatures of 10 hours stagnant water ranged from 16°C to 26°C. Earlier studies (Lautenschlager et al. 2010, Prest et al. 2013) on water quality in homes showed that the overnight stagnation of water in DDWSs can promote microbial activity in drinking water. Still, one study (Lautenschlager et al. 2010) was done in colder months, with reported temperatures of fresh water ranged from 9°C to 12°C, while for the other study (Prest et al. 2013) the temperature ranges were not reported.

The overnight stagnation of 10 hours led to increased microbial activity, i.e. up to 1.5-fold increase in ICC concentrations and up to 7-fold increase in ATP levels were measured (Figure 5-8 left), if the fresh water temperature was lower than 17°C. However, if the fresh water temperatures were higher than 17°C, the overnight stagnation of water didn't promote microbial activity. Here, on the contrary, reduction in microbial activity was observed, namely the reduction in ICC and ATP concentrations was up to 2-fold and 5-fold, respectively. This might imply bacterial re-growth had probably already happened in the distribution network, as favourable conditions had been met elsewhere, in terms of required temperature and available nutrients, leaving a limited organic carbon content that can be utilized by microbial population in DDWSs. Similar temperature influence on overnight growth pattern was also observed with HPC measurements (Figure 5-7 right). Here the critical fresh water temperature for the shift in the growth pattern was around 16°C, which coincides with the critical temperature of 17°C of ICC and ATP.

5.3.4 Biofilm measurements

The characteristics of biofilms from two different pipes, kitchen and shower, were quantified by FCM, ATP and HPC measurements.

Table 5-1 Biofilm characteristics measured by FCM, ATP and HPC measurements from-kitchen and shower tap

Biofilm sample	TCC [10^5 cell/cm^2]	ICC [10^5 cell/cm^2]	HPC [CFU/cm^2]	ATP [pg/cm^2]
Kitchen tap	6.6	2.9	6	12
Shower tap – conventional system	10	5.7	3	11

Biofilm in the shower tap contained higher amounts of total cells (TCC 10x10^5 cells/cm^2) and intact cells (ICC 5.7 x10^5 cells/cm^2) than in the kitchen tap (TCC 6.6x10^5 cells/cm^2 and ICC 2.9 x10^5 cells/cm^2, respectively). A possible reason for this could be higher ambient temperature on the 2nd floor, where the pipe is located. The amount of viable biomass and cultivable bacteria in biofilm was similar for the two pipes, 12 pg/cm^2 and 6 CFU/cm^2 for the kitchen pipe and 11 pg/cm^2 and 3 CFU/cm^2 for the shower pipe, respectively. Measured ATP and HPC concentrations are below the range of reported biofilms formed in drinking water distribution systems, which ranged from 500 to 4000 pg ATP/ cm^2 and 10^6 – 10^7 CFU/cm^2 (Boe-Hansen 2001, Kalmbach et al. 1997, Lehtola et al. 2006, Lehtola et al. 2004, Liu 2013).

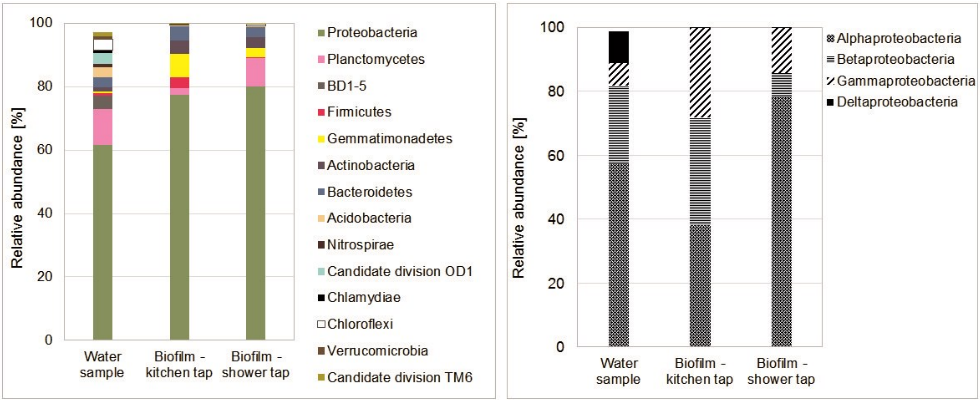

Figure 5-9 Left: Relative abundance of bacterial phyla. Right: Relative abundance of Proteobacteria classes in water from shower tap sample and biofilms sampled from kitchen and shower taps

Proteobacteria, as shown in Figure 5-9 left, were the predominant phyla in both water and biofilm samples, ranging from 61% to 80%, which has also been reported in earlier research (Eichler et al. 2006, Liu et al. 2013, Lührig et al. 2015, Magic-Knezev et al. 2009). *Protobacteria* in the water samples were represented by 57% of *Alphaproteobacteria*, 25% of *Betaproteobacteria*, 7% of *Gammaproteobacteria* and 10% of *Deltaproteobacteria*. Interestingly, a different composition of *Proteobacteria* was observed in the biofilm samples from the kitchen and shower pipes (Figure 5-9, right). In the kitchen biofilm sample *Alphaproteobacteria*, *Betaproteobacteria* and *Gammaproteobacteria* were evenly distributed (38%, 33% and 28%, respectively). In the shower tap sample the most dominant members of *Proteobacteria* were *Alphaproteobacteria* (78%), while the abundance of *Betaproteobacteria* and *Gammaproteobacteria* was considerably lower, 7% and 14%, respectively. These findings indicate that biofilms which are formed in a DDWS do not necessarily have share the composition, which might a consequence of the microclimate in homes and difference in consumption patterns at various drinking water taps.

5.4 CONCLUSIONS

- Stagnation promoted leaching of copper and zinc from pipes and fixtures both during summer and winter stagnation experiments. Maximum concentrations of both copper and zinc were reached after 48 h in winter experiments and after 24 h in summer experiments, which might be related to the seasonal differences in water chemistry.

- Stagnation of water influenced microbial activity in drinking water, whereas at low fresh water temperatures activity increase in stagnant water, while at the high fresh water temperatures activity was found to decrease with water stagnation. This implies that the re-growth of bacteria occurs mainly in distribution networks in summer months, while during winter months bacterial re-growth happens in DDWSs.
- From the analysis of biofilms it can be concluded that different biofilm compositions may exist within one DDWS, which can be attributed to the influence of the microclimate in houses and consumption patterns at different taps on biofilm formation.

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CHAPTER 6

6 INFLUENCE OF AN EXTENDED DOMESTIC DRINKING WATER SYSTEM ON THE DRINKING WATER QUALITY

Abstract

Drinking water and fire safety are strongly bonded to each other; they are both delivered through the same network (actual drinking water demand and fire flows) and are both devoted to public health and safety. In The Netherlands, the discussion about fire flows supplied by the drinking water networks has drawn fire fighters and drinking water companies together, searching for novel approaches to improve public safety. One of these approaches is the application of residential fire sprinkler systems on a large scale fed by drinking water. This approach would have an impact on the layout of domestic drinking water systems (DDWSs), as extra plumbing would be required to have the residential fire sprinkler heads installed. This experimental study investigated the influence of the added plumbing on the quality of both fresh and 10 hours stagnant water in two full scale DDWSs, conventional and extended systems (C-S and E-S). Enhanced microbial activity was observed when the fresh water temperature was lower than an observed tipping point (15°C for the HPC and 17°C for the FCM and ATP measurements, respectively). The same trend of increase and decrease in microbial activity, driven by the fresh water temperature, was observed in both systems. Characterization of microbial populations in water samples and harvested biofilms showed that among the identified sequences of phylum bacteria, *Protobacteria* were the most dominant species. High similarity between water and biofilm communities, >98% and >70%, respectively, indicates that the extension of the DWWSs does not affect the microbial quality of drinking water.

Keywords: Domestic drinking water systems, fire sprinklers, water quality, water temperature, water stagnation

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6.1 INTRODUCTION

The primary role of drinking water distribution systems is to supply sufficient drinking water quantity and quality, at adequate pressure ranges, to the consumers. Apart from that, most of the drinking water distribution networks also carry along so-called “fire flows”, which are the amounts of water necessary to extinguish fires by firefighting services. Nowadays, the usual demand of a fire hydrant, which supplies firefighting water, is in the range from 30 to 60 m^3/h, which is delivered through the network with pipes of 100 mm and larger. Additionally, the maximum allowable spacing between the hydrants and objects should not exceed 40 m in The Netherlands. These spatial and flow requirements have led to the phenomena of generously sized networks, given that a standard residential service connection rates at 1.5 to 2.5 m^3/h (VEWIN 2008). This means that majority of the distribution networks is dimensioned on fire flows rather than on the actual drinking water demands. The impact of large networks is low velocities in the networks and prolonged residence times, which may promote accumulation of sediment and related water quality issues like discoloration, low disinfectant residual and microbiological regrowth (Vreeburg 2007).

Despite the fire flows, delivered through commonly large drinking water networks, and in spite of fire safety developments in the last decades, the number of residential fires and fire fatalities remains almost constant in The Netherlands. Around 7,000 dwelling fires occur each year, leaving on average 45 dead and dozens more injured (NIFV 2001 - 2015). One of the main reasons for this trend is that the evacuation time has decreased from 17 to 3 minutes (Bukowski et al. 2007, Bukowski et al. 1975). Over 30 years ago, when the evacuation time was estimated to be 17 minutes, houses were furnished with natural materials (genuine wooden furniture, wool carpets, etc.), while most of the modern residential occupancies and their interiors are made with synthetic materials that can ignite readily and lead to the fast fire spreading and release of toxic gases. Therefore, nowadays deadly conditions are reached in as little as 3 minutes in home fires. In addition to this, statistics show that the fire services response time is around 8 minutes in The Netherlands (Gadet 2009) and once the fire brigade reaches the fire scene, it might be too late to save the lives from the hazards of fire, applying only the conventional fire flow approach.

The discussion about the fire flows supplied by large drinking water networks has drawn fire fighters and drinking water companies together, seeking for new approaches to improve public health and safety. An automatic fire sprinkler system, being one of the discussed approaches, is an active fire protection measure which does not only extend the evacuation time of residents, but also serves to the control of the fire before the fire brigade reaches the fire event and uses the water from fire hydrants. According to the statistics, automatic fire sprinklers have proven to prevent more than 80% of residential fire casualties and around 70% of property damage (Hall et al. 2012). Though the first sprinkler patent dates from 1874 (Ford 1997), their application in Europe is mostly restricted to industrial purposes. The technical problem of widespread implementation of domestic fire sprinkler systems was, up to recent years, the required water flow and pressure for a conventional fire sprinkler head, which was in order of 50 to 80 L/min and 0.7 to 1.6 bar, respectively. Latest innovations in sprinkler head design have yielded fire sprinkler heads (Zlatanovic et al. 2014), which are efficient under low flow and pressure ranges (30 L/min and 0.5 bar, respectively) which are the thresholds found at the most distant location in a typical Dutch house. With no technical barriers to cross in terms of required flow and pressure it is, nowadays, feasible to integrate sprinkler systems into domestic drinking water systems (DDWSs) in The Netherlands. Nevertheless, a sprinkler system integration into a conventional DDWS has an impact on the layout of DDWSs itself, such as increased piping diameters, extended pipe length, more volume of the system and hence, may affect the quality of drinking water at the consumers' tap. In The Netherlands the quality of the drinking water is routinely measured at the tap and the Dutch drinking water companies are responsible for the water quality from the tap, unless a poor maintenance of DDWSs is proven (Staatscourant 2011). This study aimed to determine the extent to which an implementation of a sprinkler system in DDWSs results in alteration of water quality at the consumer's taps. The foci of the study were chemical and microbial parameters of fresh and stagnant water and microbial characterization of biofilm in both conventional and extended full scale DDWSs.

6.2 MATERIALS AND METHODS

6.2.1 Description of the experimental rigs

To examine the influence of added plumbing for the installation of residential fire sprinkler heads to a conventional DDWS on water quality, two full-scale DDWSs, a conventional (C-S) and an extended (E-S) DDWSs were built (Figure 4-2, Figure 4-3 and Figure 4-4) and operated for 430 days.

Configuration of the conventional rig (Figure 4-2 and Figure 4-4) complies with the Dutch home plumbing codes NEN 1006 (NEN 2002). The conventional DDWS consists of 2 vertical lines and 4 horizontal branches of copper (manufactured in accordance with European Standard EN 1057), namely vertical copper composite of 22 mm diameter - carrying cold water to the upper floors, vertical copper tube of 15 mm – delivering hot water from a 50 L water heater and copper tubing's of 15 mm- supplying cold and hot water from the vertical lines to the 11 plumbing fixtures (solenoid valves). The total length of the pipes is 48.6 m and the volume of the plumbing rig is ~6 L. The extended system (Figure 4-3) has loops of 22 mm diameter piping on each floor, and the total length of the piping in the extended system was 116 m and the volume was ~26 L.

To be able to mimic a realistic drinking water consumption at the household level, the test rigs comprise 11 solenoid valves (point of use) per system. The valves were configured to run automatically (on and off mode) according to the one year demand patterns generated by the SIMDEUM model (**SIM**ulation of water **D**emand, an **E**nd **U**se **M**odel). SIMDEUM model, developed by KWR Watercycle Research Institute (Nieuwegein, The Netherlands), is a stochastic model which includes statistical information of water appliances and water consumers. SIMDEUM generates water demand patterns based on consumers' behavior, taking into account the differences in DDWSs and water-using appliances (Blokker et al. 2010, Blokker et al. 2006). In this research, the SIMDEUM demand patterns of a two-person household were used.

6.2.2 Drinking water

Drinking water was delivered to the experimental rigs from a drinking water company, Evides Waterbedrijf, located in the city of Rotterdam. Drinking water is produced from Meuse water from the Biesbosch reservoirs and treated by flocculation, sedimentation, ozonation, rapid sand filtration, and activated carbon filtration. Before pumping to a storage reservoir, the filtrate from activated carbon filters is treated with chlorine dioxide, 0.1 ClO_2 mg/L. Drinking water from this storage reservoir is distributed and disinfectant residual concentrations are below the detection limit. In Table 6-1 an overview of the drinking water quality parameters at the treatment facility is given.

Table 6-1 Drinking water quality parameters (minimum, maximum and average values, N – number of samples) at the treatment facility (Prest 2015a)

Parameter	Unit	min	Max	average	N
Temperature	°C	2.3	22	12.5	416
Dissolved oxygen	mg/L O_2	10.3	19.4	13.9	52
Turbidity	FTU	<0.05	0.36	<0.05	466
pH		7.79	8.32	8.08	468
Conductivity (20 °C)	mS/m	40.5	49.6	44.8	417
UV-extinction, 254 nm	1/m	1.1	2.6	2.1	27
DOC	mg/L C	1.07	1.97	1.61	28
AOC	µg/L ac-C	5.3	43	28	20
Chlorine dioxide	mg/L ClO_2	0	0.034	0.006	93
Carbon dioxide	mg/L CO_2	<1	2.8	1.9	13
Hydrogen carbonate	mg/L HCO_3	106	134	121	13
Chloride	mg/L Cl	50.7	60.2	53.5	13
Sulphate	mg/L SO_4	43	66	52	13
Sodium	mg/L Na	34	42	37	13
Potassium	mg/L K	5	6.5	5.6	13
Calcium	mg/L Ca	43.4	50	46.9	13
Magnesium	mg/L Mg	6.7	7.8	7.2	13
Hardness	mmol/L	1.363	1.538	1.463	13
Ammonium	mg/L NH_4	<0.03	0.05	<0.03	52
Nitrite	mg/L NO_2	<0.01	<0.01	<0.01	13
Nitrate	mg/L NO_3	11.2	14.6	12.8	13
Silicium	mg/L Si	1.25	3	2.1	13
Iron	µg/L Fe	<5	9	<5	36
Manganese	µg/L Mn	<5	<5	<5	4
Aluminium	µg/L Al	<10	<10	<10	13
Antimony	µg/L Sb	<1	<1	<1	4
Arsenic	µg/L As	<1	<1	<1	4
Barium	µg/L Ba	14	22	18	4
Boron	mg/L B	0.042	0.049	0.046	4
Cadmium	µg/L Cd	<0.05	<0.05	<0.05	4
Chromium	µg/L Cr	<1	<1	<1	4
Mercury	µg/L Hg	<0.03	<0.03	<0.03	4
Nickel	µg/L Ni	1	2	2	4
Selenium	µg/L Se	<1	<1	<1	4
Strontium	µg/L Sr	140	160	150	4
Bromide	mg/L Br	0.07	0.111	0.087	13

Parameter	Unit	min	Max	average	N
Fluoride	mg/L F	0.19	0.27	0.22	13
Cyanide	µg/L CN	<0.5	<0.5	<0.5	13
Bromate	µg/L BrO_3	2.3	6.8	3.6	26
Chlorate	µg/L ClO_3	<40	57	<40	13

6.2.3 Stagnation experiments

To examine the influence of overnight stagnation on drinking water quality in DDWSs, 8 months long experimental research was carried out. Prior to each stagnation experiment, which happened twice a month, water was flushed through the system by opening the solenoid valves for 5 minutes, at a flow rate between 20 - 30 L/min. After flushing the pipes samples of fresh water were collected at the inlet point, cold kitchen tap and cold shower tap. The water at the inlet (connection) point was sampled to assess the difference, if any, in fresh water quality between the inlet point and the points of use in the DDWSs, because the length of the pipe that delivers water from the connection point to the lab rigs was 40 m. After collecting the fresh water samples, water was allowed to stagnate in the drinking water plumbing rig systems for 10 hours, in order to mimic overnight stagnation of drinking water in DDWSs. After the overnight stagnation water samples (i.e. stagnant water) were taken at the kitchen and shower taps (1.05 L at the kitchen tap and 0.7 L at the shower tap from the C-S DDWS, and 1.0 L at the kitchen tap and 6.0 L – the volume of the added sprinkler loop on the first floor at the shower tap from the E-S DDWS). Stagnant water samples were collected in sterile bottles (1-10 L) and then transferred into the sampling cups for further analysis. Samples were stored on ice in a cooler for maximum 12 hours until analysis at Het Waterlaboratorium in Haarlem, The Netherlands.

6.2.4 Water and biofilm analysis

After 8 months of the stagnation experiments, systems were run for additional 6 months (total 430 days after the experimental start-up). After that period kitchen and shower pipes (3 times 20 cm long pipe specimens) were cut from the experimental rigs. The pipe specimens were filled with sterilized water and were closed by autoclaved silicone rubber stoppers and were sealed ethanol – treated parafilm. Biofilms were detached by three consequent cycles of low energy ultrasonic treatments, with 2 minutes per ultrasonication cycle, before further analysis (Magic-Knezev and van der Kooij 2004).

The biofilm results were normalized with respect to the surface area of the pipes (cm^2) and measured volume (mL). In addition to this, as statistically significant differences were observed in stagnant water quality between shower samples from the two systems, 2 fresh water samples were also taken for the analysis of the richness and diversity of microbiota in shower water samples.

After acidification with hydrochloric acid, the concentrations of copper and zinc in fresh and stagnant water were determined by Inductively Coupled Plasma mass spectrometry (ICP-MS). The detection limit of this method was 0.1 µg/L.

The content of total organic carbon (TOC) in water samples was determined in triplicates applying the combustion catalytic oxidation/NDIR method (TOC-V CPH, Shimadzu, Duisburg, Germany), which is based to the Dutch standard procedure NEN-EN-1484 (NEN 1997a), with the detection limit of 10 µg/L and the standard deviation of ±10%.

The number of culturable bacteria in water and biofilm samples was determined by the heterotrophic plate count (HPC) method which was performed following the Dutch guidelines for drinking water NEN-EN-ISO 6222 (NEN 1999), while the detection of *Legionella pneumophila* was done according to NEN-EN-ISO 6265 (NEN 2007).

The process of staining for total and intact cell counts and flow cytometry (FCM) was done for water and bacterial suspensions obtained from the biofilm samples according to the protocol described previously (Hammes et al. 2008, Hammes et al. 2011, Nakamoto et al. 2014, Vital et al. 2012).

Total ATP concentration in water and biofilm samples was measured by employing the reagent kit for bacterial ATP (Celsis; Brussels, Belgium) and a luminometer (Celsis Advance™, Celsis, Netherlands) according to the protocol described in a study (Magic-Knezev and van der Kooij 2004). The detection limit of this ATP method was 1 ηg/L.

The cultivation-independent investigation of microbial diversity and richness of water and biofilm was done by next generation sequencing at KWR in Nieuwegein, The Netherlands. Collected samples (250 mL of fresh water sample and 30-45 mL of suspensions obtain by sonication of biofilm samples) were filtered through polycarbonate membrane filters with a pore size of 0.2 µm to concentrate bacterial cells. The bacterial cells were lysed by a combination of lysis buffer and bead-beating

This was done after folding the filter and putting the folded filter in a bead tube containing BF1 and BF2 buffers of the Power Biofilm Kit (MoBio, Carlsbad, USA) lysis buffer. DNA was purified as described in the Power Biofilm protocol provided by MoBio. The V3-V4 region of the bacterial 16S rRNA genes were PCR-amplified and processed. Paired-end sequences were generated on the Illumina MiSeq system using the 2X 300 cycles protocol and paired end sequences were merged, using FLASH (Magoč and Salzberg 2011) and all subsequent analyses were performed using the version 7.5 of the Bionumerics software (Applied Maths, Sint-Martens-Latem, Belgium). Quality filtering was based on PHRED scores by excluding sequence reads with a minimal score of 20 and excluding reads with an average quality below 30. The final sequences were identified against the Silva taxonomic database (Pruesse et al. 2007, Yilmaz et al. 2014).

6.2.5 Statistical analysis

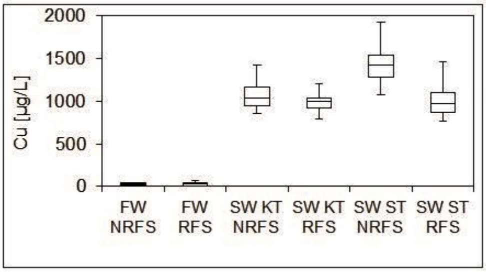
Statistical analysis was carried out to determine if the measured data sets from fresh and stagnant water (copper, zinc, HPC, TCC and ATP values) were significantly different. The data that were found to be normally distributed were tested by the t test, while in case of the non-normal distributed nonparametric tests (Kruskal-Wallis tests) were performed (Kruskal and Wallis, 1952).. The statistical analysis was done using the Minitab 17 statistical software (Minitab 2014).. In this study, differences were considered to be significant if the p-value was less than 0.05.

In order to visually summarize and compare fresh and stagnant water quality parameters for conventional and extended systems, data were plotted according to the box plot methodology. Box plot displays the mean, quartiles, minimum and maximum observations, and outliers for a group of investigated parameters (Tukey 1977).

6.3 RESULTS AND DISCUSSION

6.3.1 Overnight stagnation experiments

In Figure 6-1 measured copper and zinc concentrations in fresh and stagnant water are summarized.



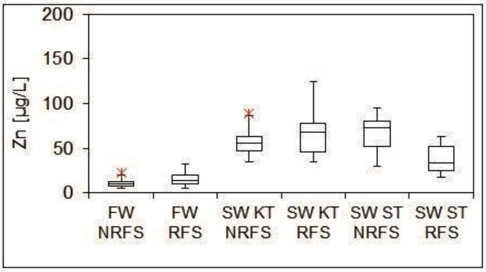


Figure 6-1 Copper (left) and zinc (right) concentrations in fresh water (FW) and stagnant water (SW) in the conventional (C-S) and extended (E-S) system at the kitchen tap (KT) and shower tap (ST). Number of fresh samples (inlet, kitchen and shower) = 48. Number of samples per tap = 16.

Kruskal-Wallis test showed that statistically insignificant difference existed with respect to the copper and zinc concentrations between fresh water samples coming from the inlet tap, kitchen tap and shower tap. Copper concentration in fresh water samples from two DDWSs was, on average, 30 µg/L (range 12-75 µg/L). As shown in the Figure 6-1, copper levels significantly increased (30-50 fold) due to the overnight stagnation of 10 hours. The copper content of the stagnant water was not significantly different between the two stagnant samples collected from the kitchen taps from the two experimental rigs, and was on average 1082±183 µg/L for the conventional system, and 996±118 µg/L for the extended system, respectively. The stagnant water from the shower tap in the conventional DDWS contained, on average, ~400 µg/L more copper than the water from the kitchen tap. This difference could be attributed to the microclimate around the experimental DDWS, as the temperature of the ambient is higher on higher floors, i.e. the ambient temperature on the 1st floor (where the shower tap is located) was 1.1 ± 0.3^{o}C higher than the ambient temperature on ground floor (where the kitchen tap is placed). For the extended system, the copper levels in the shower stagnant samples were ~450 µg/L lower than that from the conventional DDWS and were statistically different from the measured copper levels in the shower samples from the conventional rig. This lower copper content in the shower sample of the extended system can be explained by 1.5 times greater volume-to-surface ratio of the loops that deliver water to the shower tap in extended systems, meaning that smaller surface area of the pipes was accessible for the copper leaching process. Copper leaching from pipes was already reported in literature and the concentrations were strongly dependent on the stagnation time and concentration of dissolved oxygen (Edwards and Sprague 2001). Elevated copper concentrations in drinking water are known to cause acute and chronic health effects, as gastrointestinal disorders and liver damage. The World Health Organization (WHO) has set 2 mg/L as a maximum concentration value for drinking water (WHO 2004). In this research, the measured copper levels in water samples were all below the guideline value proposed by WHO.

Zinc concentration in fresh water samples from two DDWSs was, on average, 10 µg/L (range 5-33 µg/L). Similarly to the leaching of copper, overnight stagnation appeared to promote the zinc release from the brass components, which are used in drinking water distribution systems as valves, faucets and other fixings, as a 3-7 fold increase in zinc levels was measured after 10 hours of stagnation. The zinc levels in the stagnant water were not significantly different between the two kitchen stagnant samples and the shower sample from the conventional system (average 57±14 µg/L at the kitchen tap for the conventional system, 68±27 µg/L at the kitchen tap for the extended system and 68±21µg/L at the shower tap for the conventional system, respectively). For the extended system, the levels of zinc in the shower stagnant samples were ~40 µg/L lower than in the other water samples, which might be a result of the larger volume-to-surface area of the loops for the fire sprinkler system. Dezincification represents a de-alloying process which is caused by the leaching of zinc from brass components (Coker 2010). No health-based guideline value for zinc in drinking water is available, but at zinc concentrations above 3 mg/L an undesired colour and taste can develop (WHO 2003). In this research, the measured zinc concentrations in both fresh and stagnant water samples were far below the proposed aesthetic guideline.

The TOC concentration over the stagnation time is presented in Figure 6-2/

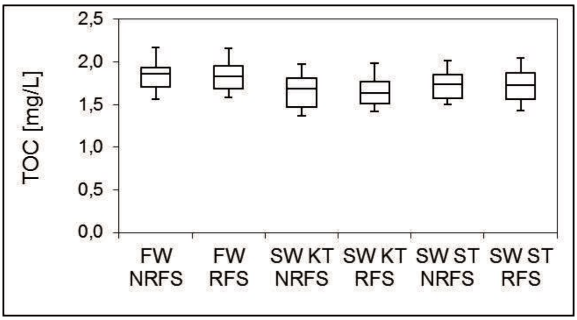


Figure 6-2 TOC concentrations in fresh (FW) and stagnant water samples (SW) in the conventional (C-S) and extended system (E-S) at the kitchen tap (KT) and shower tap.(ST). Number of fresh samples (inlet, kitchen and shower) = 48. Number of samples per tap = 16.

The average content of total organic carbon in the fresh samples was 1.80±0.16 mg/L. As it is evident from Figure 6-2, the TOC concentrations were found to decrease with 5-15% during the overnight water stagnation. This reduction in TOC content in the stagnant samples could be related to both microbial activity in water and biofilms, and adsorption of the organic matter onto pipe surfaces. The differences in TOC content in the fresh and stagnant water between the two DDWSs systems were found to be insignificant.

During the period of the experimental research, the temperatures of fresh water ranged from 6°C to 23°C. A temperature tipping point of fresh water at 15°C was observed, at which a shift in the HPC behavior was measured (Figure 6-3).

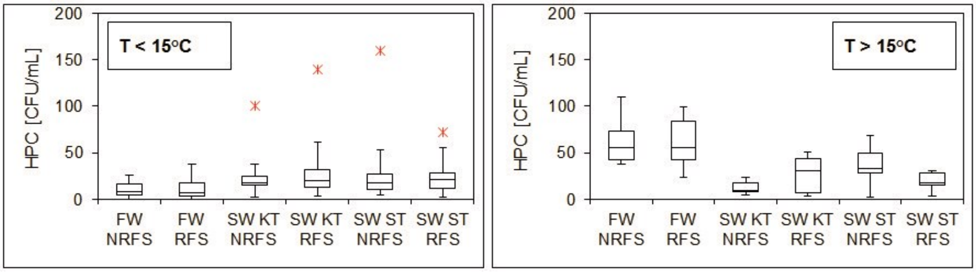


*Figure 6-3 HPC levels in fresh water (FW) and stagnant water (SW) in the conventional (C-S) and extended (E-S) system at the kitchen tap (KT) and shower tap (ST). Number of fresh samples (inlet, kitchen and shower) = 48. Left: Temperature of fresh water < 15°C, number of fresh samples = 33, number of stagnant samples per tap = 11. Right: Temperature of fresh water >15°C, number of fresh samples =15, Number of stagnant samples per tap = 5; * - outliers.*

Over the study period, the numbers of heterotrophic bacteria in fresh water samples from the conventional and extended DDWSs were similar; i.e. on average 10±7 CFU/mL was observed in water samples with temperatures lower than 15°C and 63±26 CFU/mL was measured in water samples with temperatures higher than 15°C (Figure 6-3). The numbers of heterotrophic bacteria generally increased with overnight stagnation time, i.e. up to 5-fold increase in HPC levels was measured if the temperatures of fresh water were lower than 15°C. However, when the temperatures of fresh water were higher than the tipping point of 15°C, up to 6-fold reduction in HPC was observed in stagnant water samples.

A previous research on biological stability of drinking water produced and distributed by Evides Waterbedrijf, showed that assimilable organic carbon (AOC), a portion of TOC that can be utilized by microorganisms, exhibited a reverse seasonal trend compared to the water temperature. The lowest AOC concentrations (3.5 µg/L) were measured at highest water temperature, while the highest AOC concentrations (41.4 µg/L) were detected at low drinking water temperatures at the water treatment facility (Prest 2015).

The observed shift in the activity of heterotrophic bacteria may be a direct result of seasonal variations of AOC in drinking water. With high water temperatures, low AOC content could be further reduced during the distribution, leaving the limited amount of AOC for re-growth in DDWSs. On the other hand, during the winter months with low fresh water temperatures,, favorable conditions for pronounced re-growth, in terms of temperature, could only be met in the DDWS, where the ambient temperature was 16 to 25°C.

The same trend in microbial activity was found with ATP and FCM measurements, but here the observed tipping point was 17°C. Figure 6-4 gives an overview of ATP and ICC-HNA concentrations in fresh and stagnant water samples from the conventional and the extended DDWS.

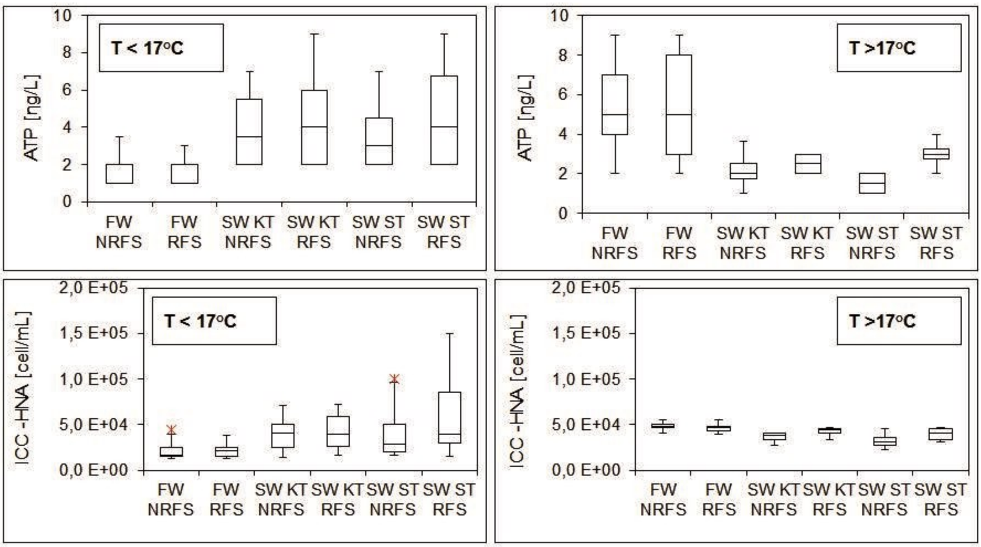


*Figure 6-4 ATP (up) and ICC-HNA (down) concentrations in fresh water (FW) and stagnant water(SW) in the conventional (C-S) and extended system (E-S) at the kitchen tap (KT) and shower tap (ST). Number of fresh samples (inlet, kitchen and shower) = 48.Left.: Temperature of fresh water < 17°C, number of fresh samples = 36, number of stagnant samples per tap = 12. Right: Temperature of fresh water >17°C, number of fresh samples =12, Numberod stagnant samples per tap = 4; * - outliers.*

The statistical difference between the ATP and ICC-HNA concentrations in fresh water samples for both investigated DDWSs was statistically insignificant ($p > 0.05$). The mean values of ATP and ICC-HNA concentrations in fresh water samples with temperatures lower than 17°C were 1.85±0.78 ηg/L and $2.1x10^4$±0.7 $x10^4$ cell/mL, respectively. The average ATP and ICC-HNA concentrations in fresh samples with drinking water temperatures higher than 17°C were 5.1±2.4 ηg/L L and $4.6x10^4$±0.5 $x10^4$ cell/mL respectively. In this research, most of the changes in measured cell concentrations after the overnight stagnation experiments were observed for ICC - HNA fraction, while ICC - LNA fraction remained stable.

Similar to the microbial activity measured by traditional HPC approach, the overnight stagnation induced microbial activity, as up to 8-fold increase in ATP concentrations was noted, when the temperature of fresh water was lower than 17°C. This observation coincides with the findings from a previous research of induced microbial activity in terms of ATP after overnight stagnation of water in DDWSs (Lautenschlager et al. 2010). On the other hand, when the temperature of the fresh water was higher than 17°C, up to 9-fold reduction in ATP concentrations was measured. The same trend of microbial activity was observed for the ICC-HNA subgroup, which is accountable for the most important part of the bulk activity in stagnant water (Lautenschlager et al. 2010), i.e. up to 4 fold increase above the tipping point of 17°C and up to 40% of reduction in ICC-HNA levels in cell numbers below the fresh water temperature of 17°C. The promoted growth of microorganisms, during the overnight stagnation was already reported in earlier research (Lautenschlager et al. 2010, Prest et al. 2013). However, the decrease in cell numbers and activity, driven by the overnight stagnation combined with elevated temperatures of fresh water, is to the knowledge of the authors a novel finding.

It is also important to point out that the differences in microbial activity, measured by HPC, ATP and FCM measurements, were not statistically significant between the stagnant samples from the kitchen taps from the two different DDWSs. The differences found between microbiological parameters in the stagnant shower water samples were statistically significant, which is probably a result of the DDWS lay-out alteration, as extra loops in E-S were added. However, the approach of flushing the pipes did "restore" the quality of drinking water, as insignificant difference was observed between all fresh water samples (inlet, kitchen and shower) taken from both systems.

Last but not the least, concentrations of opportunistic pathogen *Legionella pneumofila* in fresh and stagnant water were below detection limit of 100 CFU/mL during the whole experimental period.

6.3.2 Biofilm measurements

The characteristics of biofilms formed along the kitchen and shower pipes in the conventional and extended systems were quantified by FCM, ATP, HPC measurements and by next-generation sequencing.

Table 6-2 Biofilm characteristics measured by FCM, ATP and HPC measurements from-kitchen and shower tap in conventional and extended systems

Biofilm sample	TCC [10^5 cell/cm^2]	ICC [10^5 cell/cm^2]	HPC [CFU/cm^2]	ATP [pg/cm^2]
Kitchen tap – conventional system	6.6	2.9	6.1	12
Kitchen tap – extended system	5.4	3.3	6.9	10
Shower tap – conventional system	10	5.7	3.7	11
Shower tap – extended system	2.1	1.5	0.3	8

In the conventional system, as given in Table 6-2, biofilm in the shower pipe contained higher amounts of total cells and intact cells ($1.0x10^6$ cells/cm^2 and $5.7x10^5$ cells/cm^2.) than in the kitchen pipe (TCC $6.6x10^5$ cells/cm^2 and ICC $2.9x10^5$ cells/cm^2, respectively). The biofilm extracted from the kitchen pipe in the extended system contained similar content of total and intact cells to the biofilm from the conventional DDWS. A possible reason for more cell counts in the biofilm from the shower tap in the conventional system is less frequent water consumption and higher ambient temperature on the 2nd floor, where the pipe is located. Though unexpected, the biofilm from the shower pipe in the extended DDWS had almost 4-5 times less cells (intact and total), compared to that from the conventional DDWS, which might be due change in the lay-out (1.5 larger volume to surface ratio of the pipe delivering the water to shower tap in the extended system).

The amounts of heterotrophic bacteria and viable biomass in the biofilm samples were similar for the four pipes and were in the range from 0.3-6 CFU/cm^2 and 8 - 12 pg ATP/cm^2. The HPC results are below the range found in literature, 10^6 – 10^7 CFU/cm^2 (Kalmbach et al. 1997, Lehtola et al. 2006, Liu 2013). The results also show that less than 0.01% of the total bacteria in biofilms are culturable, estimated by the traditionally applied HPC approach, which is in line with findings from above mentioned studies that the portion of biofilm culturable bacteria is as little as 0.01 % to several percent of the total cell concentration. Measured ATP values were also below the range of reported biofilms formed in drinking water distribution systems, which ranged from 500 to 4000 pg ATP/ cm^2 (Boe-Hansen 2001, Boe-Hansen et al. 2002, Lehtola et al. 2006, Lehtola et al. 2004). Low HPC and ATP can be due to the fact that in this study water was mainly stagnant in the systems, while in previous studies water was continuously flowing through the pipes - introducing new nutrients for bacteria to grow within the biofilm phase.

Table 6-3 Number of sequences, richness, diversity and evenness indexes for water samples and biofilm samples harvested from kitchen and shower taps in conventional (CS) and extended (ES) system.

Sample	Number of sequences	OTU (97%)	Chao Index	Coverage [%]	Shannon Index	Evenness
Fresh water – shower tap – CS	185546	3122	3509	89	6.17	0.76
Fresh water – shower tap – ES	178081	3056	3480	88	6.15	0.76
Biofilm – kitchen tap – CS	115046	1144	1959	58	2.67	0.38
Biofilm – kitchen tap – ES	132662	1202	1627	60	2.95	0.41
Biofilm – shower tap – CS	79962	1313	2206	67	2.37	0.33
Biofilm – shower tap – ES	79383	736	1086	45	2.44	0.37

The number of generated sequences were ~180,000 for water samples and from ~80,000 to 130,000 for biofilm samples (Table 6-3). These high numbers of sequences helped to detect higher numbers of operational units (OTUs at a 3% cut-off., i.e. 3056 and 3122 in the water samples and from 736 to 1313 for the biofilm samples, respectively). Higher bacteriological richness was observed in the water samples than in the biofilms, Chao1 index 3480- 3509 and for water and 1627-1959 for biofilm samples, respectively. In addition to this, it was found that the coverage for water samples was 88-89%, while for the biofilm samples coverage was found to be lower, namely 45-67%.

Biofilm formed along the kitchen pipes in both DDWSs had similar bacterial abundancy, while the biofilm harvested from the shower pipe in the extended system, had the lowest richness, which is probably a result of the DDWS lay out alteration. According to the Shannon index, fresh water samples contained higher microbial diversity than the biofilm samples, 6.15 - 6.17 and 2.37 – 2.95 respectively. The other diversity parameter, evenness, showed that the species were more evenly distributed in the drinking water samples than in the biofilms. The other diversity parameter, evenness, showed that the species were more evenly distributed in the drinking water samples than in the biofilms. Lower evenness in biofilm might be related to specialisation in biofilms, or that certain species are more abundant.

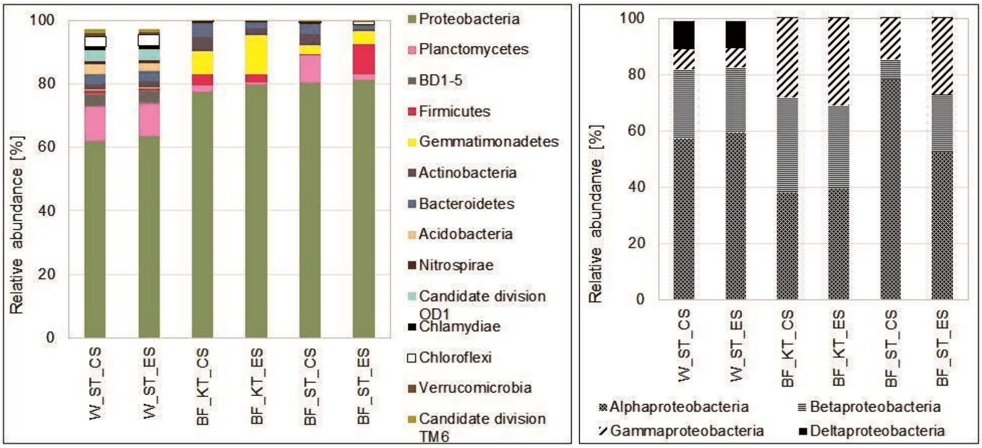


Figure 6-5 Left: Relative abundance of bacterial phyla. Right: Relative abundance of Proteobacteria classes in water from shower tap samples (W_ST) and biofilms (BF) sampled from kitchen (KT) and shower taps (ST) in conventional (C-S) and extended system (E-S)

As is evident from Figure 6-5*, Proteobacteria* were found to be the predominant phyla in both water and biofilm samples, ranging from 61% to 81%, which has also been reported in earlier research (Eichler et al. 2006, Liu et al. 2013, Lührig et al. 2015, Magic-Knezev et al. 2009). *Proteobacteria* in the water samples were represented by 57% of *Alphaproteobacteria*, 25% of *Betaproteobacteria*, 7% of *Gammaproteobacteria* and 10% of *Deltaproteobacteria*.. Among the remaining phyla in the water samples, *Plancomycetes* were the second most dominant bacteria, accounting for 10% of the total, while the abundances of *BD1-5*, *Candidate division OD1*, *Chloroflex*, *Acidobacteria* and *Bacteroidetes* were < 3%. Slightly different composition of *Protobacteria* content was observed for the biofilm samples and was as follows: 29-62% of *Alphaproteobacteria*, 5-26% of *Betaproteobacteria*, 11-24 % of *Gammaproteobacteria*. Biofilm samples had also a little different abundances of the remaining phyla, i.e. 3-12 % of *Gemmatimonadetes*, 0.1-9% of *Firmicutes* , 1-4%of

Bacteroidetes, 0.6-4% of *Actinobacteria*. Sequences related to anoxic bacteria *Firmicutes* were dominant (~9%) among the other phylum bacteria for the biofilm extracted from the shower pipe biofilm in the extended system.

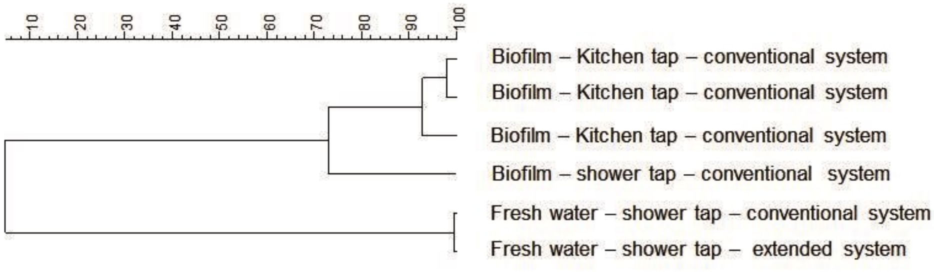


Figure 6-6 UPGMA Pearson correlation for the biofilm and water samples at genus level.

A distance analysis (**U**nweighted **P**air **G**roup **M**ethod with **A**rithmetic Mean method - UPGMA), presented in Figure 6-6, shows that there is a high similarity between the fresh water samples and biofilms for both systems at the genus level, >98% and >70 - 94%, respectively. These high similarities suggest that the extension of the copper DDWS did not significally affect neither the microbial quality of fresh water, nor the biofilm composition in the examined systems.

6.4 CONCLUSIONS

- Overnight stagnation of water in the C-S DWDS and E-S DWDS promoted leaching of copper and zinc from the copper pipes and brass elements. However, the measured copper and zinc concentrations in stagnant water samples were all below the maximum contaminant levels proposed by WHO.
- Significant differences in water quality were observed between the stagnant water samples from the shower taps in the C-S and E-S. Insignificant differences between all fresh water samples were found for all examined parameters, meaning that the tap flushing can restore the quality of the drinking water quality in DDWSs.
- Change in microbial activity was evident after the overnight stagnation in both systems, while the trend of the activity appeared to be a function of fresh water temperature. At low fresh water temperatures activity increased, while at the high fresh water temperatures activity decreased.
- Characterization of the microbiota in the water samples and biofilms showed that among the identified sequences, *Proteobacteria* were the most dominant phyla.

High similarity at the genus level between fresh water and biofilm communities for both systems, >98% and >70 -94% respectively, indicates that the extension of the DWDS does not affect neither microbial water quality, nor the biofilm compositions..

- Extension of the copper DWDS for residential fire sprinklers had limited effect on drinking water quality parameters, during the 14 months of the experimental study.

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CHAPTER 7

7 CONCLUSIONS AND RECOMMENDATIONS

The principal goal of this thesis was to develop and assess the feasibility of an additional residential fire safety measure, a fire sprinkler system that is integrated into DDWSs. The research had the following specific objectives:

1. To develop design criteria for a fire sprinkler system that operates under low flow and low pressure thresholds typically found in Dutch houses.
2. To develop and validate a model which predicts the water temperature dynamics in DDWSs.
3. To evaluate the importance of the two water quality surrogate parameters, temperature and stagnation time, with regard to the quality of the drinking water
4. To study the influence of the added plumbing for the sprinkler integration on the water quality and biofilm in DDWSs.

7.1 RESEARCH NOVELTIES

Key novelties of this research are:

- Development of the design criteria for a sprinkler head that is efficient under low flow and low pressure conditions;
- Modelling of residence time and temperature in DDWSs;
- First time experimenting with two full scale DDWSs, that were run according to the stochastic water demand patterns, following the water quality analysis over time and under different water temperatures.

7.2 DESIGN CRITERIA FOR A LOW FLOW AND LOW PRESSURE FIRE SPRINKLER SYSTEM

Minimizing the impact of residential fires on fire damage and number of fatalities is feasible with the installation of automatic sprinkler systems. Still, because of the flow and pressure demands for conventional fire sprinklers, which are in the range from 50 to 80 l/min and 0.7 to 1.6 bars, respectively, the application of fire sprinkler systems on a large scale is limited to industrial purposes in The Netherlands. As a starting point in this research, evaluation of the sprinkler performance, in terms of the repression efficiency, was carried out by adding a drop combustion sub-model to the deterministic model of the atomization process. The outputs of the adjusted model, Theoretical Heat Capacity (THC), Evaporate Heat Capacity (EHC) and Specific Heat Capacity (SHC), revealed that the overall sprinkler performance is not directly proportional to the supplied flow and pressure, but depends on the drop size and the number of the drops in a screen. The experimental investigation into the characteristics of the initial drop screen showed that initial spray characteristics are greatly influenced by the geometry of the sprinkler head, under given hydraulic operational conditions. In combination with the measured drop size distribution of the spray formed under low flow and low pressure ranges, the combustion sub-model indicated that it is possible to achieve a comparable performance as under higher flows and higher pressure ranges. Overall, it can be concluded that with a breakthrough in the sprinkler head design, it is feasible to have a fully functional fire sprinkler system which can be directly connected to the DDWS.

Recommendations: Following these findings, TU Delft in collaboration with Bam Techniek, VSH Fitting, Brandweer Haaglanden has successfully developed a sprinkler head (“waterleidingsprinkler”) that is suitable for the Dutch houses and is expected to be applied on a large scale in the coming years. Additional real fire testing, under various residential fire scenarios, was done separately from the current research, to prove the effectiveness of the developed sprinkler in practice. One of the recommendations for further research is to build a computational fluid dynamics (CFD) model to simulate the interaction between the tested residential fires and spray delivered by low flow and low pressure fire sprinklers.

7.3 A TEMPERATURE MODEL FOR DDWSS

Water temperature, being one of the rate controlling parameter for many chemical and microbiological processes, is considered as a surrogate parameter for water quality processes in the water distribution phase. Measuring of temperature at the tap point level is not only time consuming but is also associated with high costs for drinking water companies. Having this in mind, a drinking water temperature model that predicts the temperatures at each point of use DDWSs was developed and validated, using the measurements from the two full scale experimental DDWSs. Based on the statistical analyses, it is concluded that the drinking water temperature model is able to reproduce the temperature profiles within a copper DDWSs. Both model and experimental results showed that the water temperature dynamics in homes is mainly driven by the water consumption pattern and ambient temperature, and is limitedly dependent on the size and layout of the DDWSs. Moreover, the results revealed that drinking water is being warmed up by 0.5 to 2°C within the copper DDWSs, namely from the inlet point to the tap in use, depending on how far from the inlet point the demand takes place. Therefore, if the drinking water temperature is determined by sensors in drinking water distribution networks, the temperatures at the points of use can be underestimated.

Recommendations: In the conducted research, DDWSs made of copper were used for the model validation. Because the model is based on fundamental thermodynamic principles, it can be used for other DDWSs pipe materials as well. Nevertheless, the applicability of the model for other pipe materials commonly applied in DDWSs needs to be experimentally evaluated, which is one of the recommendations for future research. The next step would include coupling of the temperature model for DDWSs with a model that predicts the temperature of the water in the drinking water distribution system, aiming to model the temperature dynamics from the treatment facilities (reservoirs) to the points of actual water use (drinking water taps in DDWSs).

7.4 INFLUENCE OF WATER STAGNATION TIME AND TEMPERATURE ON DRINKING WATER QUALITY IN DDWSS

The quality of the drinking water alters while it is being transported through the distribution system. DDWSs, as the final component in the drinking water supply chain, are the most critical locations at which quality may be affected, given the long stagnation times and elevated temperatures. Water stagnation showed to affect both the chemical and microbial quality of water in DDWSs. From a chemical perspective, water stagnation was found to promote leaching of copper and zinc from pipes and fixtures. Microbial properties of stagnant water from DDWSs (HPC, ATP and ICC), on the other hand, were found to differ under winter and summer conditions, whereas the microbial activity in the stagnant water was mainly related to the temperature of the inlet fresh water. At low temperatures of the inlet water, activity increased during the overnight stagnation, while at the high inlet water temperatures, activity was found to decrease in the stagnant water samples, according to the measurements. This phenomenon implies that the promoted bacteriological activity occurs in the water network in summer months, while during winter months the majority of the bacterial development takes place in DDWSs. Moreover, from the differences that were found in water quality parameters and formed biofilms between the samples from two investigated taps (kitchen and shower), it may be concluded that the micro-climate in homes (ambient temperature distribution) and water consumption patterns also affect the quality parameters of stagnant water and biofilms.

Recommendations: Organic carbon is most often the growth limiting factor for microbiota in drinking water. This research included only measurements of total organic carbon, with no further assessment of AOC and other growth limiting substrates, which can be utilized drinking water bacteria. Therefore, it would be worthwhile to carry out a similar research, with the focus on the growth limiting substrates and their influence on the microbial activity in DDWSs during the stagnation of water in winter and summer months. Also, the micro-climate in houses, and its influence on the drinking water quality/biofilms, along with the demand patterns of a particular tap, might be interesting areas of study recommended for future researches.

7.5 INFLUENCE OF ADDED PIPING IN DDWSS FOR FIRE SPRINKLER ACCOMMODATION

Integration of residential fire sprinkler systems into DDWSs on a large scale has an impact on the layout of DDWSs, as extra plumbing is required to have the residential fire sprinkler heads installed. Though some differences in water quality were observed between the stagnant water samples from the shower taps in the conventional and extended systems, insignificant differences between all fresh water samples were found for all examined parameters, meaning that the tap flushing can restore the quality of the drinking water quality in both systems. It is concluded that the extension of the DWDS for residential fire sprinklers had limited effect on drinking water quality parameters, during the 14 months of the experimental study.

Recommendations: In this research, the influence of added plumbing loops for sprinkler installations on water quality was evaluated in two DDWSs made of copper. It would be valuable to determine if other pipe materials which are commonly applied in DDWSs, have similar effect on the microbial parameters of the stagnant water and biofilms. Moreover, no actual sprinkler heads were mounted in the experimental rig of the extended system. A following step in research should include examination of the influence of sprinkler heads themselves on the quality of the drinking water, due to the possible dead volumes between the plumbing and the sprinkler heads.

7.6 PRACTICAL CONSEQUENCES

The first part of this thesis was devoted to the development of the design criteria for a novel fire sprinkler system, which can be directly connected to the DDWSs. From the results gathered in this thesis it was concluded that it is possible to achieve comparable sprinkler efficiency under low flow and pressure, as under higher ranges of operational flow and pressure, which was, indeed, a novel perspective in a fire sprinkler world. After this new insight, TU Delft has in collaboration with Bam Techniek, VSH Fitting, Brandweer Haaglanden developed a sprinkler head ("waterleidingsprinkler") that is suitable for the Dutch houses. The fire experiments showed that residential fires can be safely contained in a small area by use of the low flow and low pressure sprinklers and the evacuation time was greatly prolonged (even up to 45 minutes since the beginning of a fire). The property damage was only related to a minimal water damage. Therefore, in addition to the energy label, every house should have a fire safety label too, which is dependent on the evacuation time and potential fire damage, in case of a residential fire. In that way, having a residential sprinkler system, would add a value to the house on the market. It is also worthwhile to mention, that by fighting a fire in this manner, large fire flows of 30 m^3/h, which are supplied by hydrants, may not be necessary in the future in full amount, if the sprinkler systems are applied on a large scale. A possible reduction in the design requirements for fire flows would certainly have an impact on the layout of the water distribution networks, as smaller pipe diameters would be needed. This would, in turn, improve the velocity distribution in drinking water networks, and eventually improve the quality of the drinking water.

In The Netherlands, drinking water companies are responsible for the quality of water at the consumers' taps; unless it can be proved that the owner did not maintain the DDWS in a proper way. In order to be sure that drinking water at the tap meets legal requirements, statuary monitoring of the delivered water is performed by water companies. This is done through a random daytime (RDT) measurement program. However, most of the sampling methods include flushing the taps before the RDT sampling, and thus the effect of water stagnation in DDWSs is not taken into consideration when evaluating the safety of drinking water and compliance with Dutch drinking water legislation. On the other hand, many people do consume water directly from the tap without prior flushing of the DDWS.

Water companies advise to flush DDWSs, but only after a long period of stagnation (more than 7 days). This advice seems to be based on an intuitive approach rather than on scientific facts, as only limited research has been carried out in the past years on the effect of stagnation in DDWSs. In this thesis it was concluded that stagnation does not necessarily lead to the induced microbial activity. During summer months microbiological activity appears to happen mainly in distribution networks, while during winter months most of the activity happens in DDWSs. However, more research is needed on stagnation effects in DDWSs which would, among others, contribute to the knowledge on the required frequency of DDWS flushing. Moreover, with these new insights, very strict rules in installation design may be a bit loosened, opening new possibilities for applications of innovative technologies, such as integration of sprinkler system in DDWSs.

8 APPENDIX

Appendix A: MSX code

```
[TITLE]
Temperature modeling for household drinking water systems

[OPTIONS]
RATE_UNITS      SEC
SOLVER          EUL
COMPILER        NONE
TIMESTEP        5

[SPECIES]
BULK            T_water         MG
BULK            AGE             MG

[COEFFICIENTS]
CONSTANT        gg              9.81            ;m/s^2     gravitational acceleration
CONSTANT        rho_w           1000            ;kg/m^3    water density
CONSTANT        rho_a           1.205           ;kg/m^3    density of air
CONSTANT        cp_w            4185            ;J/(kg K)  heat capacity of water
CONSTANT        mu_w            0.001           ;Pa s      dynamic viscosity-water
CONSTANT        mu_a            0.000018        ;Pa s      dynamic viscosity-air
CONSTANT        kv_a            0.000000000216  ;m^2/s     kinematic viscosity of air raised
by power two
CONSTANT        alpha           1.36e-7         ; m2/s     diffusivity coefficient-water
CONSTANT        Pr_w            8.09            ;-         Prandtl number-water
CONSTANT        Pr_a            0.7372          ;-         Prandtl number-air
CONSTANT        lambda_w        0.589           ;W/(m K)   thermal conductivity of water
CONSTANT        lambda_a        0.02476         ;W/(m K)   thermal conductivity-air
CONSTANT        beta_a          0.00349         ;1/K       cubic expansion coefficient
CONSTANT        d_air           0.005           ;m          air layer around encapsulated
pipes
CONSTANT        tt              3600
CONSTANT        minus            -1             ;-         help variable
PARAMETER       T_env           14.5            ;K         environment temperature
PARAMETER       lambda_p        403             ;W/(m.K)   thermal conductivity -copper
pipes
PARAMETER       vv              1               ;-         help parameter: equals 1 for
vertical pipes
PARAMETER       L               1               ;-         length of vertical pipe

[TERMS]
;Nusselt number for moving fluid
Nu              step(10 - Re)*5.8 + step(Re - 10)*step(2300 - Re)*3.66 + step(Re -
2300)*(0.023*Re^0.8*Pr_w^(0.3333))                              ;step function for
calculation Nusselt number of water (stagnant, laminar and turbulent flow)
h_1             Nu*lambda_w/D
h_2             lambda_p/(D*0.1)        ;pipe wall is assumed to be 10% of pipe diameter
Ra_a            gg*beta_a*(T_env - T_water)*D*D*D*Pr_a/kv_a             ;step function for
calculation Rayleigh number for horizontal or vertical geometry
Nu_a            step(0 - Ra_a)*minus*0.59*Ra_a^(0.25) +  step(Ra_a - 0)*0.59*Ra_a^(0.25);step
function to avoid root of negative number in calculation Nusselt number for air
h_3             Nu_a*lambda_a/D
```

```
h_comb          1/(1/h_1+1/h_2+1/h_3)                                  ;thermal      resistance
concept
kk              4*alpha*h_comb/D

[PIPES]
RATE            T_water                     kk*(T_env - T_water)        ;K water temperature
RATE            AGE                         1 / tt

[SOURCES]
SETPOINT        4               T_water         60

[QUALITY]
GLOBAL          T_water         14.5
GLOBAL          AGE             0
NODE            1               T_water         9
NODE            4               T_water         60

[PARAMETERS]
;list of pipes which are horizontal
;list of pipe lengths (vertical pipes)
;list of pipes which are influenced by T_env (i.e. throughparallel hot water pipes)

[REPORT]
SPECIES                 T_water         YES
SPECIES                 AGE             YES
```

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10 ABOUT THE AUTHOR

Ljiljana Zlatanović was born on 29th of March 1982 in Aleksinac, Serbia. In 2009, she obtained a Master's degree in Civil Engineering at University of Niš, Faculty of Civil Engineering, Niš, Serbia, with a specialization in Hydraulic and River Engineering with a thesis titled "Conceptual design of river "Pusta reka" stream banks at village Pukovac, municipality of Niš, Serbia". After graduating she got a full scholarship for the Master Course in Municipal Water and Infrastructure at UNESCO-IHE, Institute for Water Education, Delft, The Netherlands. She graduated in 2011 with a thesis "Optimization of IHE Arsenic Removal Technology Based on Adsorption and InSitu Regeneration". From November 2011 she has worked on her PhD research at Delft University of Technology, Water Management Department, under the supervision of prof Jan Peter van der Hoek and Jan Vreeburg. The research focused on residential fire sprinklers and water quality in domestic drinking water systems. From January 2016 to January 2017 she worked as a network analyst at Water company Vitens, Zwolle, The Netherlands. Since January 2017 she works as a researcher at Delft University of Technology, Water Management Department and AMS Institute.

List of publications and contributions

Peer-reviewed::

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