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Drinking Water Temperature Modelling in Domestic Systems

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Abstract

Domestic water supply systems are the final stage of the transport process to deliver potable water to the customers' tap. Under the influence of temperature, residence time and pipe materials the drinking water quality can change while the water passes the domestic drinking water system. According to the Dutch Drinking Water Act the drinking water temperature may not exceed the 25°C threshold at point-of-use level. This paper provides a mathematical approach to model the heating of drinking water within the domestic water supply system. It appears that residence time influences the drinking water temperature more than the ambient temperature itself.

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Keywords: Drinking water quality; temperature; domestic systems; point-of-use; SIMDEUM

1. Introduction

Domestic water supply systems are the final stage of the transport process to deliver potable water to the customers' tap. The domestic water supply system is defined as the drinking water infrastructure between the water meter (connection to drinking water distribution network) and point-of-use (tap). Under influence of water temperature, residence time and pipe material the drinking water quality may change while the water passes the domestic drinking water system. According to the Dutch Drinking Water Act the drinking water temperature may not exceed the 25°C threshold at point-of-use level. Hence the drinking water companies are responsible for the drinking water quality at point-of-use level, unless they can prove that the domestic water supply system is not properly managed or constructed.

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Temperature is one aspect of water quality. However, there is still no quantification of the temperature behavior of drinking water after entering the domestic water supply system. The aim of this study was therefore to develop a temperature model for the domestic water supply system.

In former research, a model was developed to calculate the drinking water temperature in the drinking water distribution system [1]. It appears that the water temperature downstream in the drinking water distribution system equals the soil temperature at pipe depth because the residence time is longer than the heating time. Hence, it can be assumed that the temperature at which the water enters the domestic water supply system is equal to the soil temperature around the drinking water distribution system.

A model was developed for the Dutch plumbers organization to calculate the required pipe insulation for drinking water pipes in pipe shafts to prevent temperatures above 25°C [2]. In this model, the water is assumed to be stagnant. However, point-of-use demands cause water motion in the supply system. For proper calculation of water temperature an approach is needed which takes into account both the influence of time and water displacement. By using SIMDEUM [3] together with a pipe network model of a domestic water supply system demand patterns can be modelled at tap level. This creates the possibility to model realistic pipe flows in a domestic water supply system. The hydraulic conditions were calculated using EPANET. The Multi-Species Extension EPANET-MSX [4] (hereafter referred to as 'MSX') was used to implement the equations for heat transfer. The model build-up is schematized in Fig. 1.

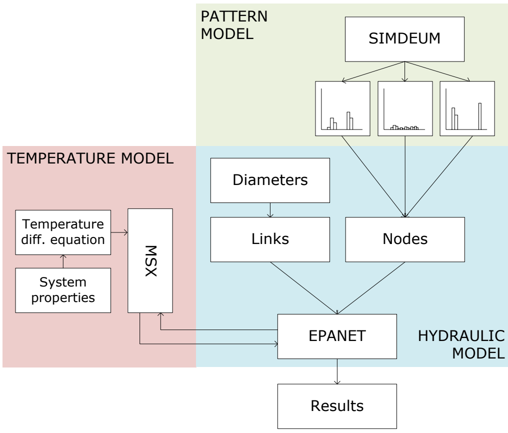

Fig. 1.Model build-up.

2. Heat transfer equation

To calculate the temperature for dynamic flow conditions in the water supply system both the temporal temperature change and spatial temperature change must be known. The temperature change in space is driven by advection. The advection is calculated by MSX. MSX uses a Lagrangian approach (i.e. 'follows' water parcels through the system) [3]. The temporal temperature change is driven by the temperature difference between water temperature inside the pipe and ambient temperature outside the pipe. The change in time can be calculated by solving the energy balance over a control volume with arbitrary length Δx for timestep Δt:

$$E_{T,t+\Delta t} - E_{T,t} = \Delta E_T \tag{1}$$

where $E_{T,t}$ and $E_{T,t+\Delta t}$ [J/m] represent the thermal energy content in the control volume at respectively time t and Δt and ΔE_T [J/m] equals the change of energy in the control volume during Δt. By substitution of the control volume geometry and the physical properties of water and taking the limit of Δt to zero the following differential equation could be obtained:

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

where T is the actual temperature (averaged over the pipe diameter)[K], T_∞ the ambient temperature [K], $h_{overall}$ the overall heat transfer coefficient [$W.m^{-2}.K^{-1}$] which represents the rate of heat transfer from pipe surrounding air to the water in the pipe, ρ the water density [$kg.m^{-3}$], c_p the heat capacity of water [$J.kg^{-1}.K^{-1}$] and D the pipe diameter [m]. Solving the differential equation with boundary condition $T_{t=0} = T_0$ yields:

$$T = T_\infty - (T_\infty - T_0)e^{-at} \tag{3}$$

where a equals:

$$\frac{4h_{overall}}{\rho c_p D} \tag{4}$$

Equation 2 can be implemented in MSX.

2.1. Defining the overall heat transfer coefficient

The overall heat transfer coefficient, can be obtained using the thermal resistance concept which means different heat transfer processes in series can be summed. The heat transfer processes could be split up in three different components: convective heat transfer inside the pipe, conductive heat transfer through the pipe wall and convective heat transfer outside the pipe. These components can be modelled as thermal resistances in series (see Fig. 2).

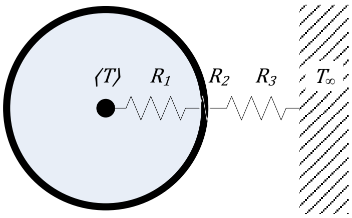

Fig. 2. Thermal resistance concept.

Hence the overall thermal resistance equals $R_{overall} = R_1 + R_2 + R_3$. The temperature is averaged over the pipe diameter and therefore denoted as <T>. Since the heat transfer coefficient is the reciprocal value of the thermal resistance R the overall heat transfer coefficient equals:

$$h_{overall} = (h_{water}{}^{-1} + h_{wall}{}^{-1} + h_{outside}{}^{-1})^{-1} \tag{5}$$

where h_{water}, h_{wall} and $h_{outside}$ are the heat transfer coefficients [$W.m^{-2}.K^{-1}$] for respectively the convective heat transfer from inner pipe surface to the water, the conductive heat transfer through the pipe wall and the convective heat transfer from surrounding air to the outer pipe surface.

2.2. Heat transfer from inner pipe wall to water inside pipe

The extent to which heat can be added to the drinking water in the pipe depends on the flow conditions, the pipe diameter and the thermal conductivity of the water. Since water is a fluid medium, the heat transfer from pipe wall to water is convective. The heat transfer coefficient for this process equals:

$$h_{water} = \frac{\lambda_w Nu_w}{D} \tag{6}$$

where λ_w equals the water thermal conductivity [$W.m^{-1}.K^{-1}$] and Nu_w the Nusselt number for water. The Nusselt number Nu_w is defined by the Reynolds and Prandtl numbers. The Reynolds number depends on pipe diameter, viscosity and flow velocity and follows from EPANET. The viscosity is assumed to be constant for the relevant temperature range. The Prandtl number can be assumed to be constant for the relevant temperature range and equals 7. A stepfunction was used to make the model valid for stagnant, laminar and turbulent flow [5]:

$$Nu_w = \left\{ \begin{array}{cc} \mathrm{Re} < 10 & 5.8 \\ 10 < \mathrm{Re} \le 2300 & 3.66 \\ \mathrm{Re} > 2300 & 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \end{array} \right\} \tag{7}$$

2.3. Heat transfer outer pipe surface to inner pipe surface

The rate of heat transfer through the pipe wall depends on the pipe material and wall thickness. Heat is transferred through a solid medium and the heat transfer is therefore a conductive process which heat transfer coefficient equals:

$$h_{wall} = \frac{\lambda_p}{d_p} \tag{8}$$

where λ_p equals the pipe thermal conductivity [$W.m^{-1}.K^{-1}$] and d_p the pipe wall thickness [m]. The pipe wall thickness d_p is assumed to be 10% of the pipe diameter as d_p is not defined in EPANET.

2.4. Heat transfer surrounding air to pipe wall

The heat transfer from surrounding air to the outer pipe wall depends on the air flow conditions around the pipe. Heat transfer from the surrounding air to the pipe surface takes place through natural convection which is driven by the buoyancy force. The heat transfer coefficient equals:

$$h_{outside} = \frac{\lambda_a Nu_a}{D} \tag{9}$$

where λ_a equals the air thermal conductivity [$W.m^{-1}.K^{-1}$] and Nu_w the Nusselt number for air.

The Nusselt number for natural convection is generally described by the product of the Grashof and Prandtl numbers, which yields the Rayleigh (Ra) number [6]:

$$Nu_a = \alpha(Gr \cdot \mathrm{Pr})^{\gamma} = \alpha Ra^{\gamma} \tag{10}$$

where α and γ are coefficients which are experimentally determined. In this model approach, all pipes are treated as vertical plates and hence $\alpha = 0.59$ and $\gamma = 0.25$ [6]. The Grashof number can be determined by:

$$Gr = \frac{g\beta(T_\infty - T_s)G^3}{\nu^2} \tag{11}$$

where g is the gravitational acceleration [$m.s^{-2}$], β the expansion coefficient [K^{-1}], T_s the temperature of the outer pipe surface [K], ν the kinematic viscosity [$m^2.s^{-1}$] and G the length [m] of the characteristic geometry. The characteristic geometry G is orientated perpendicular to the working direction of the gravity force. Hence the characteristic geometry equals the pipe length for vertical pipes and the pipe diameter for horizontal pipes. Since the air flow around pipes develops while flowing, Nusselt numbers usually are averaged along the characteristic geometry. for which the Nusselt number equals [6]:

$$Nu_a = 0.59 Ra^{0.25} \tag{12}$$

Substituting equations 6, 8 and 9 in equation 5 equals:

$$h_{overall} = D \cdot (\lambda_w{}^{-1} Nu_w{}^{-1} + 0.1\lambda_p{}^{-1} + \lambda_a{}^{-1} Nu_a{}^{-1}) \tag{13}$$

Equation 13 can be substituted in equation 2.

3. Network layout

A standard domestic water supply system was used to demonstrate the model. The network layout is shown in Fig. 3. The point-of-use locations are listed in the attached table.

#	Group	Tap points
1	Water meter	N.A.
2	Ground floor toilet	Toilet, wash basin
3	Kitchen	Kitchen tap (C,H) Dishwasher
4	1st floor toilet	Toilet
5	Bathroom	Shower (C,H) Wash stand (C,H)
6	3rd floor	Washing machine Central heater (at check valve)

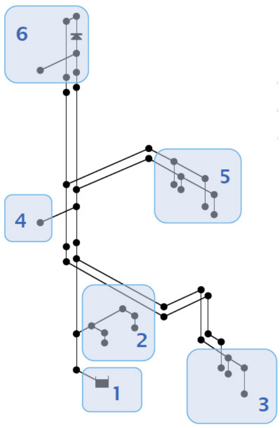

Fig. 3. Network layout of simple domestic water supply system. Numbers do correspond with rows in attached table. The addition "(C,H)" indicates a cold and hot water supply at the tap location. Locations without this addition do only have a cold water supply.

4. Scenarios

Several scenarios were evaluated with the model. Because the model is not validated yet, the model results can only be judged relatively. The model results are therefore compared to a reference case. In this reference case the ambient temperature equals 18°C and the inflow temperature equals 5°C, which are typical values for the Dutch winter season. In some scenario's an ambient temperature above 25°C was used to research the effects on the drinking water temperature inside the pipes. Ambient temperatures above 25°C can occur in summer seasons or due to so-called 'hotspots'.

Hotspots are places where the temperature of the water in the domestic water supply system exceeds the Dutch legal threshold of 25°C. These situations might occur when hot water pipes of e.g. district heating or floor heating are installed close to drinking water pipes for cold water. In Table 1 the scenarios are listed.

Table 1. Modeled scenarios using the water temperature model. Locations refer to Fig. 3.

No.	Scenario	Specification
0	Reference case	$T_0 = 5°C$, $T_\infty = 18°C$.
1	High ambient temperature (summer day)	$T_0 = 18°C$, $T_\infty = 28°C$.
2	High ambient temperature in pipe shaft	$T_0 = 5°C$, $T_\infty = 35°C$ for pipes between location 1 and 4
3	High ambient temperature single pipe	$T_0 = 5°C$, $T_\infty = 35°C$ for single pipe at location 1

5. Hydraulic conditions

The hydraulic conditions are driven by differences in head between inflow point (water meter after home connection) and point-of-use after opening the tap. Hence, the pipe flow in the system is caused by the demands at the locations shown in Fig. 3.

Demands were modeled using SIMDEUM (SIMulation of water DEmand, and End Use Model) [3]. For sake of clear comparison, only one SIMDEUM pattern was used to test the model. The total flow of this pattern is shown in Fig. 4. This pattern belongs to a small household consisting of two persons who would be at home during the day.

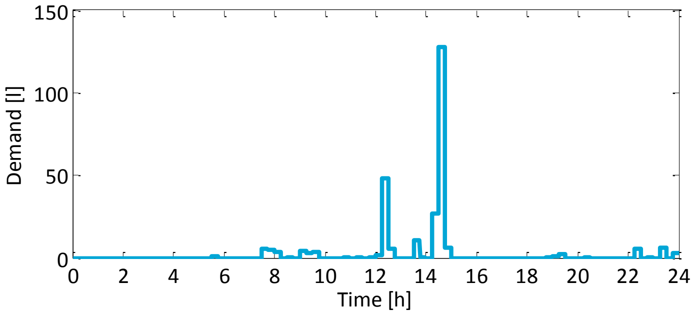

Fig. 4. Demand pattern used to create flow in the EPANET network.

6. Results

6.1. Influence of scenario no. 2 at shower and kitchen tap

Fig. 5 shows the drinking water temperature and tap volumes at the cold inlet of kitchen and shower tap in the reference case (scenario 0) compared to the hotspot scenario with pipe shaft heating (scenario 2). The influence of the hotspot is most clearly visible at the kitchen tap because cooling trajectories are visible caused by small demands (<10 liter). In the shower graph, two peaks are visible. These two are caused by drinking water which is heated in the pipe shaft before reaching the shower tap. Once this heated water is flushed from the supply system cool water from the drinking water distribution network reaches the tap creating a temperature drop.

Hotspots were modelled at several different locations. The simulations show that the location of the hotspot influences the drinking water temperature at point-of-use. The extent to which the water is heated by a hotspot depends on the residence time of the water in the network. The residence time at any point in the network depends on the demand downstream of that point. The effects on water temperature could be less in case of a frequent demand downstream of a hotspot. This will not prevent the occurrence of drinking water heated above the threshold of 25°C, however, it does prevent long residence times of water with temperature above 25°C.

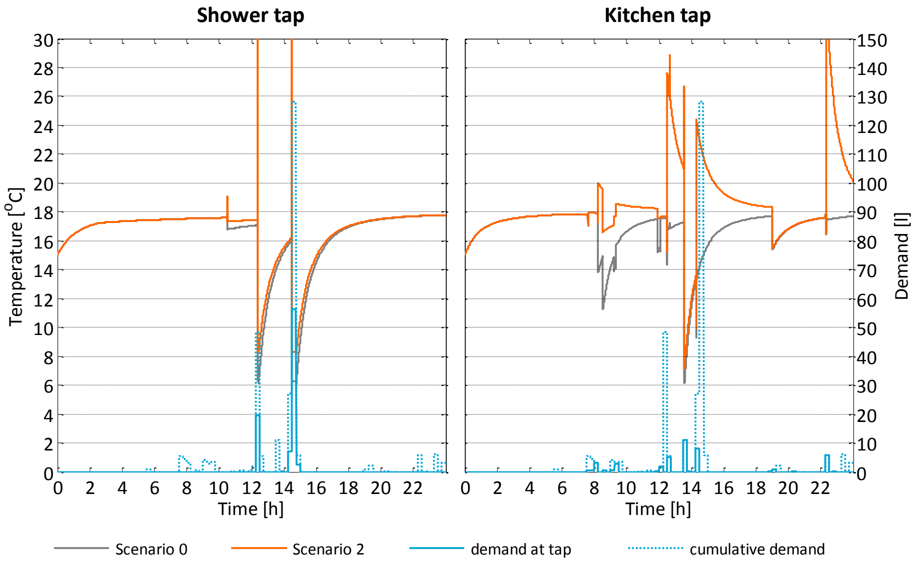

Fig. 5. Cold-water temperature at kitchen and shower tap in scenario 0 compared to scenario 2 (hotspot in pipe shaft). The cumulative demand (blue dashed line) represents the total demand in the system (Fig. 4).

6.2. Physical contact with heated water in scenario's no. 0-3

In Fig. 5 the drinking water temperature at two tap locations (shower and kitchen tap) is plotted against time for scenario 2. The question can rise to which extent water which is heated above 25°C (and thus potentially has worse quality) is actually used for consumption or showering. Fig. 6 shows the cumulative distribution of drinking water temperatures which occur at the kitchen and shower tap during demand for scenario's 0-3. The distribution of temperatures at the kitchen tap is more widely spread than at the shower tap. This is caused by the smaller tap volumes drawn from the kitchen tap compared to the tap volumes drawn from the shower tap. One large tap volume (shower) means a temperature of $T \neq T_0 + \delta$ during start of demand but most of the time a temperature of $T = T_0 + \delta$, whereas for lots of small volumes (kitchen tap) the temperature equals $T = T_\infty - \delta$ to $T = T_0 + \varepsilon$ (where δ and ε are small undefined quantities).

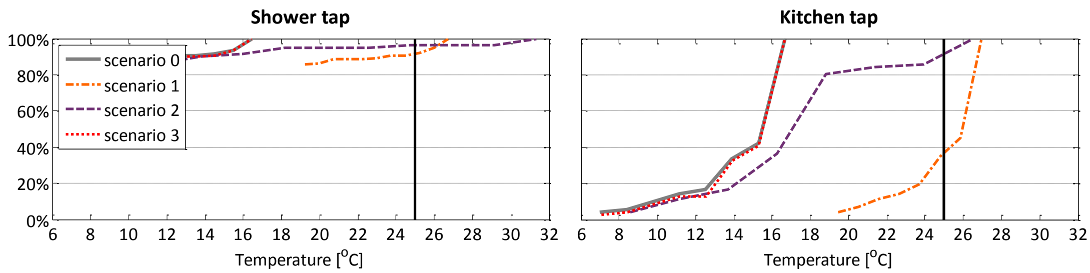

Fig. 6. Cumulative distribution function of cold-water temperatures during demand for several scenario's wherein the drinking water temperature exceeds the 25°C threshold.

The system volume of cold water pipes between inflow point and shower tap equals 3.8 liters. Assuming a tap flow of 0.167 l/s this amount is flushed away in less than 30 seconds.

For both the shower and kitchen tap one small hotspot at location 1 (scenario 3) hardly influences the temperature during demand since the difference between scenario 0 and scenario 3 is negligible. An overall ambient temperature of 28°C (scenario 1) appears to be worse compared to extreme local ambient temperatures of 35°C (scenario 2) especially for small demands at the kitchen tap.

6.3. Effects on temperature sampling at customers' tap

In Fig. 5 (grey line) it can be seen line that the drinking water temperature at point-of-use is not equal to the temperature of the water at inflow point (T_0). This means the water is heated by the pipe surrounding air while it flows from inflow point to demand point (tap). Dutch water companies take statutory water samples for water quality checks. One of the components of sampling is the measurement of temperature, which is measured at the most frequently used tap after flushing the pipe between tap and home connection. One assumes that the constant temperature which is measured after flushing equals the temperature of the water in the drinking water distribution network. However, the actual temperature in the drinking water distribution network will be lower because the water is heated between inflow point and point of measurement. This effect is the largest in winter season when the temperature difference (ambient temperature – inflow temperature) is at its maximum. Moreover, flowing water warms faster than stagnant water through eddies along the pipe wall. These turbulences stimulate the convectional heat transfer from pipe to water. Both effects result in a temperature increase of 1-2°C between water meter and kitchen tap; which create errors in the measurement of temperature.

In the pilot study larger diameters were modelled than commonly used in the Netherlands. Therefore a number of calculations with smaller diameters was performed. The results of these additional calculations show deviations between 2-4°C. For smaller diameters, the flow rate will be higher for the same water demand because the contact time is reduced. At the same time however, there is more contact between water and pipe wall. The latter effect has more influence than the former.

7. Discussion

A model was developed to calculate the temperature change of drinking water in the domestic water supply system. By coupling the model to any temperature-dependent quality model, the temperature model is appropriate to study water quality in the domestic water supply system. A second application is the calculation of energy losses of hot water pipes.

This study shows that high ambient temperatures combined with long residence times lead to an exceedance of the Dutch 25°C threshold. Residence time seems to have more influence than the ambient temperature.

It also appears that the water temperature between water meter and kitchen tap changes significantly, especially in winter season.

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