COMFORT ASSESSMENT OF TANKLESS WATER HEATERS: REVIEW AND SUGGESTIONS

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Abstract

Today, a European standard procedure for the assessment of the comfort properties of domestic hot water modules is not available. Preliminary work on this subject is existing, though: Several years ago, the Swiss research institute SPF has suggested a procedure regarding the withdrawal capacity, energy efficiency and comfort, which is sometimes regarded as preliminary state-of-the-art version of an upcoming standardization procedure to be defined in the future. On this background, this paper discusses strategies for the assessment of the comfort properties of domestic hot water modules in terms of the control performance of adopting tapping events. The assessment is based on recorded temperature data, numerically damped by a simulation model for a generic pipe section. This model yields tapping temperatures, which are assessed by means of comfort criteria regarding both the temperature value as well as its rate of change. As tapping comfort measure, we propose the heat fraction during the first 60 seconds of a tapping event that is described as "*comfortable*" as a comfort figure.

Keywords: comfort assessment, domestic hot water modules, tankless water heaters, pipe model, perception

1. Introduction

Tankless water heaters (or instantaneous water heaters) are widespread domestic hot water (DHW) supply systems, which are known as electric instantaneous water heaters, gas-fired combi boilers, DHW modules or dwelling stations (Fig. 1). Typical energy resources such as electricity, natural gas or hot water, are used to deliver the domestic hot water (or according to European Standard (DIN EN 806-1, 2001) potable hot water (PWH)).

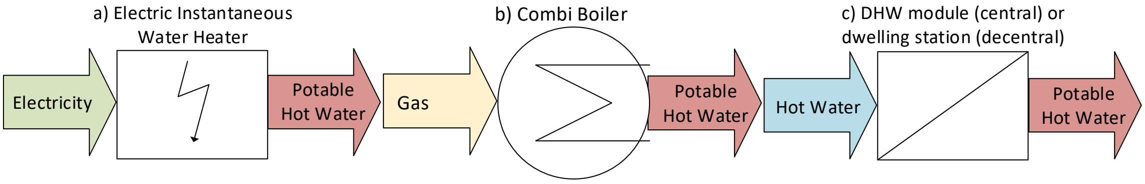

Fig. 1: Schematic of different tankless water heaters according to their energy carrier: (a) electrically supplied, (b) gas-supplied and (c) hot water supplied.

Tankless water heaters in general comprise small stagnant potable hot water volumes in the system such that accumulations of chemical and biological substances (i.e. heavy metals, bacteria ...) are less critical. German standards reflect this by allowing the operator to reduce the PWH temperature from ≥60 °C to ≥50 °C, if the water is exchanged completely within 3 days (see (DIN 1988-200, 2012)). If the volume from the water heater to each tap is less than 3 liters, the operator may even reduce the temperature below 50 °C (see (DVGW W551, 2004)) in favor of the reduction of thermal losses along the supply line (boiler/heat pump, storage, distribution network). In any case, the installer and operator must avoid stagnation of potable water (see (DIN EN 1717, 2011)), as well as critical heat transfer into the potable cold water supply (PWC) (see (VDI/DVGW 6023, 2013)) along the pipe network.

This paper focusses on DHW modules (DHWM) using hot water as energy resource at the primary (heat supply) side of the heat exchanger. Most findings are also valid for other designs of tankless water heater systems. Fig. 2 shows the system integration of a generic electronic DHWM within shaded area besides exterior system components.

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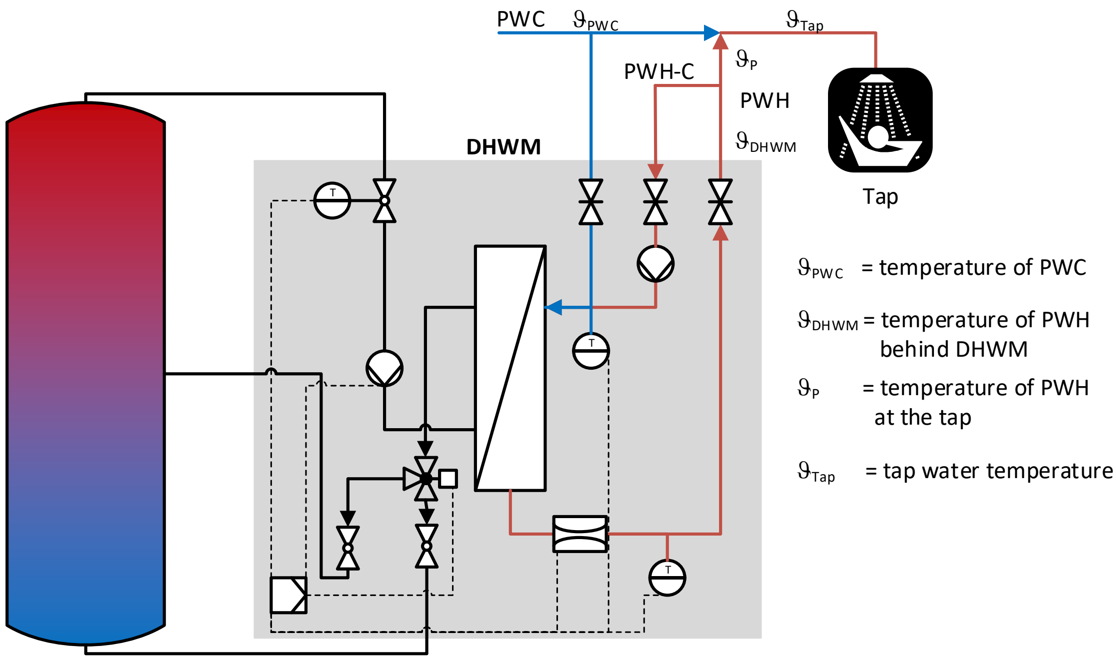

Fig. 2: Schematic of a generic electronic DHW module (DHWM) with buffer storage

The pipe lines in this figure are labeled according to standard (DIN EN 806-1, 2001). The DHWM provides potable hot water (PWH) almost instantaneously with heat taken from the buffer storage. During tapping, the user adds potable cold water (PWC) at the tap to his needs. When circulation is used, the circulation pump returns the potable hot water (PWH-C) to the DHW module, which covers the thermal losses of the distribution net. A controller modifies the pump speed according to the required heat flow rate on the secondary side.

The main challenge of DHW modules is to provide the same level of tapping comfort as conventional storage water heaters. DHW modules make use of electronic, hydro-mechanic or thermal controllers, partly in combinations for this purpose. Regarding the control strategy, DHW modules may be divided into feedforward and feedback control systems.

Feedforward controllers (see Fig. 3) typically employ hydro-mechanical or electronic systems. If electronic, the control algorithm relies on a sophisticated model considering some of the disturbances of the DHW module for setting the primary flow rate. Feedforward controllers hence do not regard differences between set-point and secondary outlet temperature. In order to obtain a minimal deviation, these models must be very accurate and any off-model effects need to be minimized by design.

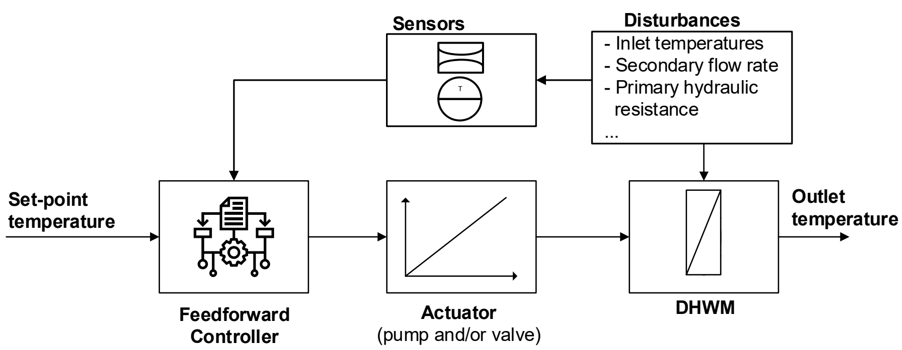

Fig. 3: Block diagram of a feedforward control system for a DHWM

Feedback controllers (see Fig. 4), in contrast, can adjust the secondary outlet temperature with respect to set-point deviations. In order to achieve a shorter settling time, the controller may measure multiple disturbances like secondary flow rate or temperatures and react according to their progressions. A known drawback of feedback controllers is the handling of system-immanent dead times, which results mainly from heat exchanger capacitive effects and the fluid content. Typical dead time may be quite high, especially for small flow rates at the secondary side of the heat exchanger, which in turn may lead to undesired temperature fluctuations at the water tap.

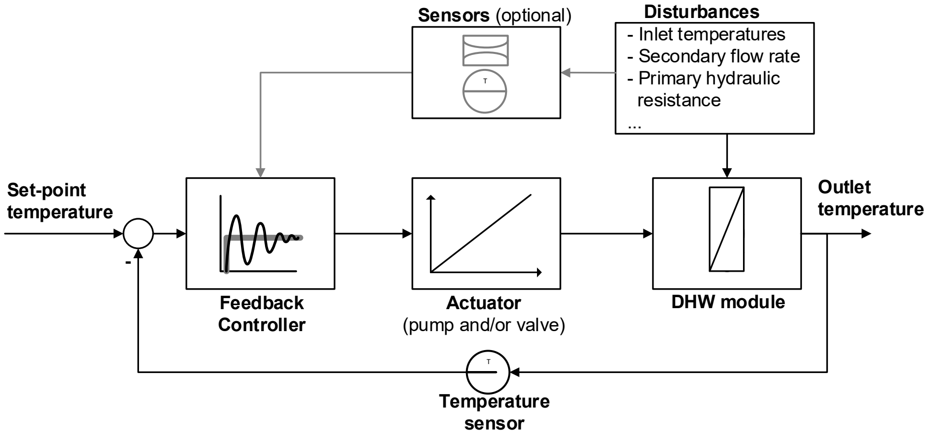

Fig. 4: Block diagram of a feedback control system for a DHWM

2. State of the Art

Providing a stable secondary outlet temperature certainly is the most important challenge in developing DHW modules and, thus, making hot water supply comfort a very important quality aspect. Proper assessment measures should also consider capacity and energy efficiency, which may establish competing design targets. For example, a manufacturer may choose a powerful primary pump to achieve a desired capacity, which in turn may lead to a lower pump efficiency (especially at smaller loads) and to a lower resolution of primary flow rate. Or else, an enlargement of the heat exchanger size increases its capacity, but this also increases the dead time, inducing consequences for the loop control strategy used.

Today, there is no official standardized test procedure for the assessment of DHW modules at European level, although there exists a test method for small DHW modules, proposed by the Swiss research institute SPF in Rapperswil. The test method considers comfort as well as efficiency and capacity (see (Ruesch and Frank, 2011a), (Ruesch and Frank, 2010)), based on measurements in a test facility with calibrated sensors. Improvements of the SPF method have been recently addressed by ISFH (see (Lampe, 2017), (Lampe and Bölter, 2017)) extending the SPF method by means of a usability measure, see Fig. 5.

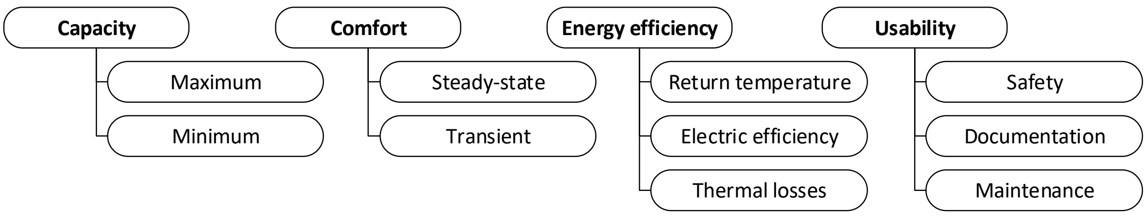

Fig. 5: Four assessment measures for small DHW modules according to ISFH work

The following paragraphs briefly review the most relevant research on the topic concerning the assessment measures employed.

2.1. Capacity

The maximum withdrawal capacity of DHW modules depends on the operating temperatures and the hydraulics. It is measured for an outlet temperature at the secondary side of 45 °C or 60 °C, while the inlet temperature at the primary side is 10 K higher. The first operating point (55/45/10 °C) applies for single family houses only, but for apartment buildings and non-residential buildings 70/60/10 °C is more relevant.

In a test situation, the maximum withdrawal capacity is detected once the measured and accuracy-corrected secondary outlet temperature drops below the set temperature. A limit for the pressure losses of the secondary side today are absent. Possible definitions must reflect the design of taps and pipe network.

Likewise the maximum capacity measure, a minimum capacity may be defined in order to regard two important aspects, the minimum flow rate of the flow sensor and the minimum thermal power of the primary side, causing lower stability of the outlet temperature if the demand falls below, e.g. operating at circulation (PWH-C). The respective value appears to be highly dependent on the inlet temperature of the primary side, which for example becomes more critical for solar thermal supply systems.

2.2. Energy Efficiency

The energy efficiency of a DHW module system in comparison to storage water heaters exhibits three additional energy consumptions:

1. Auxiliary heater: The efficiency of the auxiliary heater decreases if its return temperature rises, e.g. a heat pump by 2 %/K or a condensing boiler by 0.3 %/K. The return temperature to the buffer storage may be higher compared to the temperature of the potable cold water in the lower part of a storage water heater. Additionally, flow velocity at the storage inlet may be higher, causing temperature mixing and more start-stop operation of auxiliary heater.
2. Actuators, sensors and controllers: Electric power consumption of actuators, sensors and controllers. As high-efficient pumps are dominating the market, the standby-electricity consumption will be the most important figure.
3. Thermal losses of the DHW modules: These become relevant if the DHW module is operating with circulation (on primary or secondary side) or with a tapping demand around the clock, keeping it on high temperature. Note that some designs show limited insulation (e.g. only heat exchanger, only pipes), especially DHW modules intended for installations in flats. On the other hand, the thermal losses are even lower than the reference system, if the temperatures are significantly lower.

2.3. Comfort

The comfort assessment is related to the quality of the control system. SPF suggests criteria for both steady state and transient conditions (taking into account disturbances caused by tapping events). Fig. 6 shows a schematic of the related test procedure under transient flow conditions. Common flow disturbances are applied to the DHWM, causing the outlet temperature to fluctuate. These temperature fluctuations are both damped in the pipe between the module and the tap and at the tap itself. Eventually it is up to the sensations of the subject at the tap to decide whether these fluctuations are sensed as comfortable or not.

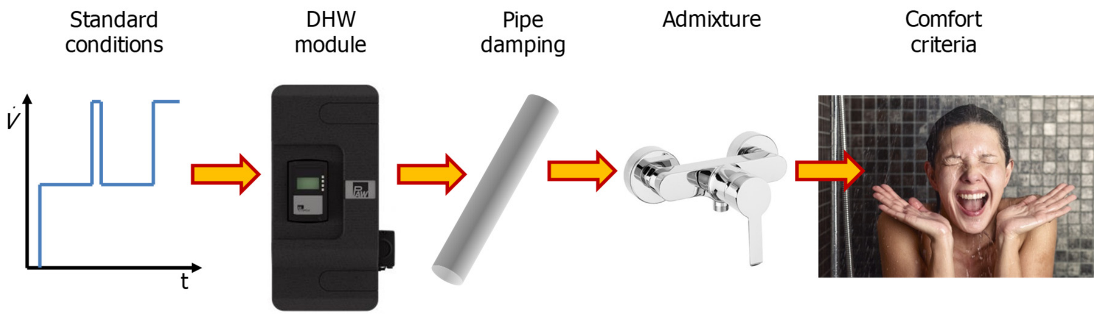

Fig. 6: Procedure for the comfort assessment regarding transient flow conditions (photo: Lars Zahner – stock.adobe.com)

According to the guideline (VDI 6003, 2012) and the European standard (DIN EN 13203-1, 2015, p. 13203) the temperature fluctuation is “uncomfortable” if the water temperature varies more than 2 K in magnitude.

The cited works (Ruesch and Frank, 2011a), (Lampe and Bölter, 2017) employ comfort visualizations by use of colored bar charts, like the one shown in Fig. 7. It visualizes the system response during the first 60 s for variable tapping events (flow disturbance). Below 2 K and 1 K the results are assessed as comfortable (green or dark green color), above 5 K as very uncomfortable (red) and in between as uncomfortable (yellow).

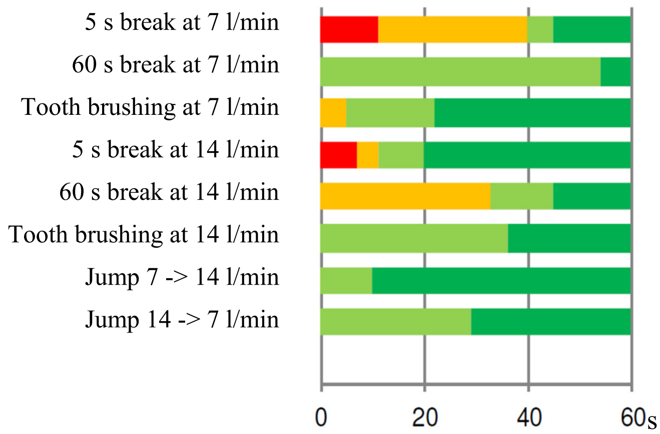

Fig. 7: Visualization of the comfort of the first 60 s after different tapping events at 70/60/10 °C (from (Ruesch and Frank, 2012))

While this visualization form implies suggestive interpretation of a system, it is difficult to identify improvements in controller development or to compare different products. Therefore, the manufacturer PAW GmbH & Co. KG has suggested to quantify the comfort by using a comfort index $f_{Comfort}$ (see (Pärisch, 2017)). For individual tapping events (index *i*), this comfort index is calculated as ratio of the amount of heat for comfortable tap water and the total amount of heat drawn from the system during the first 60 s after a disturbance occurs.

$$f_{Comfort}(i) = \frac{\int \dot{Q}_{comfortable}(i)dt}{\int \dot{Q}(i)dt} \qquad \textbf{Eq. 1}$$

This figure punishes strong overshooting temperature fluctuation. An overall comfort ratio $f_{Comfort}$ is defined as average value of all disturbances. This value should achieve values of at least 75 %, meaning that the settling time is shorter than 15 s.

The definition of the comfort ratio is different from the integral of the square of the error (ISE), that is sometimes used to describe control accuracy (see e.g. (Yuill, 2008), (Yuill et al., 2011)). As the approach of the comfort assessment is to quantify the comfort level, rather than control accuracy.

$$ISE = \int_{t=0}^{t=60s} \left(\vartheta_{Tap} - \vartheta_{Tap,set}\right)^2 dt \qquad \textbf{Eq. 2}$$

This figure has the disadvantage that it delivers values that are hard to interpret and are more related to the control accuracy rather than quantifying the level of comfort. Furthermore it punishes feedforward controllers that have a small deviation between real ϑ_{Tap} and desired set point temperature at the tap $\vartheta_{Tap,Set}$.

At steady state, temperature fluctuations may occur, if either the heat demand drops below the minimum capacity, or the primary side becomes non-linear, e.g. if the check valve is partly open. Under transient testing, possible control disturbances are due to variations of the flow rate at the secondary side, its secondary inlet temperature (especially under circulation operation), as well as the inlet temperature at the primary side. Decentral DHW modules for dwellings additionally have to cope with varying differential pressures at the primary side in situations where risers are shared. Variable hydraulic resistance for central DHW module is expected in situations where DHW modules are connected as cascade with joint supply pipes. Out of this complexity, recent projects (Ruesch and Frank, 2011a), (Lampe and Bölter, 2017) on this topic are focusing on flow rate variations only.

As standardized tapping profiles for storage water heaters are not applicable, SPF has defined a tapping profile, which is a combination of realistic tapping events (see Fig. 8). E.g. interruptions (5 s, 60 s) for soaping and shaving or load changes due to parallel usage of different taps. The first 12 min are only for conditioning purposes.

For a unique tapping temperature ϑ_{Tap} of 42 °C (by definition) three distinct flow rates at the tap $\dot{V}_{Tap}$ of 3, 7 and 14 l/min are regarded respectively. As the set point temperature $T_{DHWM,Set}$ of the DHW module is higher than 42 °C, the flow rate through the DHW module is calculated using eq. 3, depending on set point temperature $T_{DHWM,Set}$ of 45 and 60 °C and cold water temperature ϑ_{PWC} of 10 °C (see dotted line in Fig. 8).

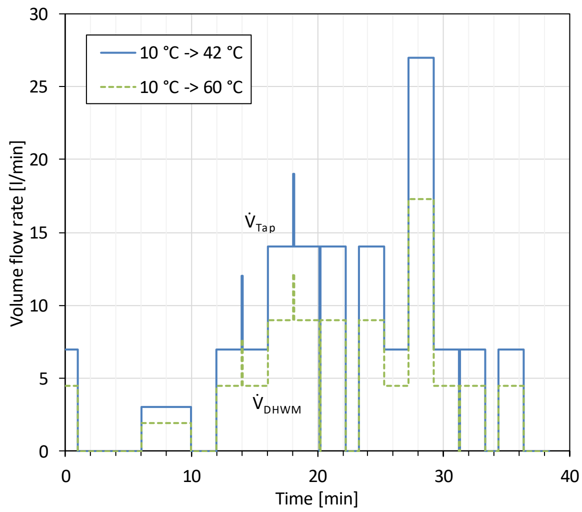

Fig. 8: Tapping profile and flow rate passing the small DHW module (dotted line)

$$\dot{V}_{DHWM} = \dot{V}_{Tap} \cdot \frac{\vartheta_{Tap} - \vartheta_{PWC}}{T_{DHWM,Set} - \vartheta_{PWC}} \qquad \text{Eq. 3}$$

The flow temperature at the primary side is set to 10 K above the set point temperature. In a second step, SPF suggests to perform a second test at 90 °C primary inlet temperature, which has shown to cause the biggest challenge for the controller. This setting was chosen with respect to solar thermal supply scenarios in summer, for example.

After applying the tapping profile, a pipe section between the DHW module and the tap damps the temperature fluctuations exiting the DHW module ϑ_{DHWM}. To account for the damping effect of the pipe between DHWM and tap, mostly numerical approaches are used. A real pipe or a mixing pot would pose the risk of interacting events. A very time-consuming initialization in front of every event would have to prevent from interaction. Furthermore, numerical methods like a pre-calculated lookup table or a pipe model (see Fig. 9) give more flexibility regarding pipe parameters.

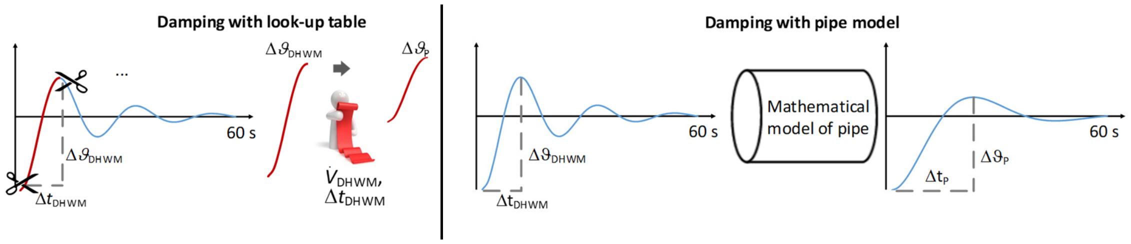

Fig. 9: The method for damping the outlet temperature of the DHW module by use of look-up tables (left) or by a mathematical pipe model (right)

SPF used a TRNSYS model (Type 604) elaborated by Thermal Energy System Specialists (TESS) (Thornton et al., 2012) with modified Nusselt equation for the calculation of lookup tables, which correlate the damping with different operational conditions (different flow rates and –durations). The model has been validated by lab measurements (Ruesch and Frank, 2011b). The results show that the damping is not depending on amplitude $\Delta\vartheta_{DHWM}$, but instead on the duration Δt_{DHWM} and flow rate $\dot{V}_{DHWM}$. Each 60 s period after a disturbance is dissolved in several rising or falling temperature progressions (see Fig. 9 left), which is very time-consuming.

These temperature progressions experience damping depending on the transport parameters $\dot{V}_{DHWM}$ (volume flow rate) and Δt_{DHWM} (duration), neglecting the interaction of rising and falling temperature progressions. However, the validity of the lookup-tables may be doubted for transient flow conditions, as the shape of a temperature progression is not periodical. Furthermore, the outlet temperature signals may experience elongations, which is neglected by the look-up tables. And finally, the look-up tables published so far do not cover the entire range of application.

Therefore, PAW proposed an alternative route to deal the situation of transient flow conditions. A sophisticated pipe model reads each 120 s sequence of the recorded outlet temperature of the DHWM. The same model (Type 604) is used, as it has been validated by SPF (Ruesch and Frank, 2011b) and NREL (Backman and Hoeschele, 2013). It regards the capacities of fluid, the pipe section and the insulation, as well as heat transfer in axial and radial direction, see (Pärisch, 2017) for a mathematical description. The initial temperature is the steady state solution with the set temperature ($T_{\mathrm{DHWM,Set}}$).

At the tap the user adds cold water ϑ_{PWC} to the hot water ϑ_{P} that is leaving the pipe, in order to adjust the desired tap water temperature ϑ_{Tap}, which is canonically assumed as 42 °C. The model assumes further constant mixing ratio of warm and cold fluxes, based on the steady state hot water temperature $\vartheta_{\mathrm{DHWM},\infty}$ of the DHW module. In case of a feedforward controller this steady state temperature may deviate from the set point temperature $T_{\mathrm{DHWM,Set}}$ according to the module characteristics. In contrast to feedback controllers, where the steady state will be within a small tolerance to the set point temperature $T_{\mathrm{DHWM,Set}}$.

The mixing process effects additional attenuation of the temperature fluctuations leaving the pipe.

When using the SPF damping method, each rising or falling temperature fluctuation leaving the tap $\Delta\vartheta_{\mathrm{Tap}}$ is calculated by use of Eq. 4:

$$\Delta\vartheta_{Tap} = \Delta\vartheta_P \cdot \frac{\dot{V}_{DHWM}}{\dot{V}_{Tap}} \qquad \textbf{Eq. 4}$$

The flow ratio may be expressed with temperatures according to Eq. 5:

$$\frac{\dot{V}_{DHWM}}{\dot{V}_{Tap}} = \frac{\vartheta_{Tap} - \vartheta_{PWC}}{\vartheta_{DHWM,\infty} - \vartheta_{PWC}} \qquad \textbf{Eq. 5}$$

Applying the method of PAW, which incorporates a pipe model, the temperature signal over a test duration of entire 60 s after individual tapping events is taken into account according to Eq. 6:

$$\vartheta_{Tap} = \vartheta_P \cdot \frac{\dot{V}_{DHWM}}{\dot{V}_{Tap}} + \vartheta_{PWC} \cdot \frac{1 - \dot{V}_{DHWM}}{\dot{V}_{Tap}} \qquad \textbf{Eq. 6}$$

The comfort at the tap hence is assessed with respect to this temperature fluctuation. PAW proposes the use of temperature rates for this purpose, rather than absolute temperatures used by SPF, claiming that temperature rates would correspond more accurately to human temperature sensations and being easier to evaluate automatically (Pärisch, 2017).

3. Suggested comfort assessment procedure

The methods proposed for the comfort assessment procedures under transient flow conditions require some adjustments before further standardization can be achieved. Current test procedures focus solely on several use-cases, where especially some definitions for testing of larger DHW modules are missing. Circulation has thus far not been part of any test procedure. And the translation of the temperature fluctuation into a comfort figure lacks scientific approach. A new proposal by ISFH for a standardized test procedure for the comfort assessment is given in this chapter, using identical steps as the previous test procedures, which have been described in chapter 2.

3.1. Tapping profile

SPF's tapping profile is composed of 10 tapping events and has a maximum withdrawal capacity of 27 l/min. Therefore, this tapping profile is not applicable to bigger DHW modules, limiting the range of application. We suggest the use of a scalable tapping profile according to Fig. 10: After an initial conditioning period, this tapping profile proceeds with a small showers' section. It comprises increasing and decreasing tapping steps of ±7 l/min with intermediate events (a tap opening of 5 l/min (for 5 and 20 s) and a shower break of 5 and 60 seconds, respectively). This test section is followed by a big showers' section with steps of ±14 l/min with the same intermediate events (unmistakably, not repeating tapping events that occurred before). In between the tapping events a measuring period of 120 seconds is induced to provide enough time for the DHW module to reach steady-state. The first 60 seconds are being used for the comfort assessment. The proposed sections of the tapping profile scale with the withdrawal capacity of the DHW module.

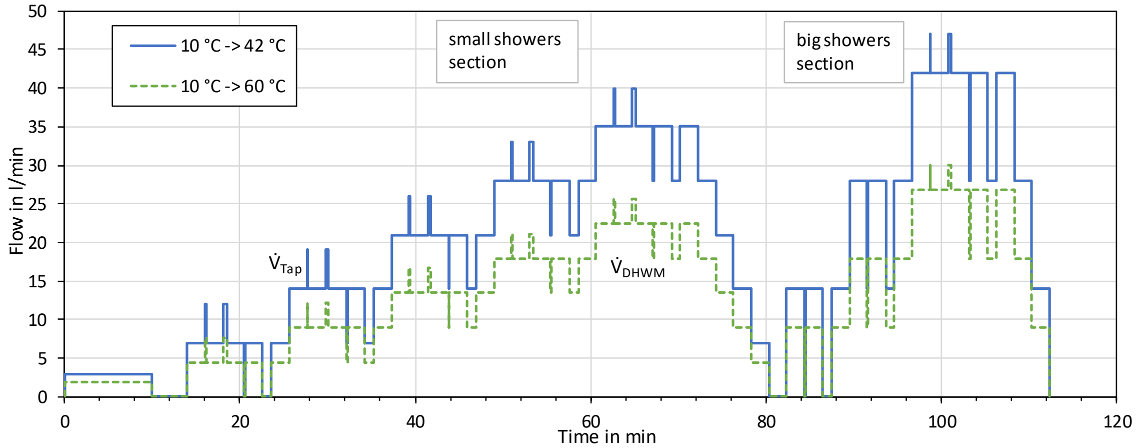

Fig. 10: Tapping profile proposal for a DHW module for apartment buildings

3.2 Test conditions

For standardization purposes, the following boundary conditions are proposed:

- Hydraulics

The flow resistance of the primary circuit of the test facility needs to be defined. Hydraulic resistances are proposed in Table 1. The feed pump of the DHW module has to exceed the pressure loss along the hydraulic loop that supplies the primary side of the heat exchanger. The hydraulic resistance may be defined with regard to the size of the DHW module. We propose to select the pipe diameter and length with respect to the size of the DHW module according to Table 1. The respective flow velocity is then in the range of 1 m/s.

Table 1: Definitions of hydraulic resistance of primary side

DHW module	**DN 15**	**DN 20**	**DN 25**	**DN 32**
Typical capacity / l/min	≈30	≈50	≈80	≈120
Pipe / mm x mm	28 x 1.5	35 x 1.5	42 x 1.5	54 x 2
Length / m	2	3	4	6
→ C / mbar/(m³/h)²	3,1	1,5	0,8	0,4

- Tapping profile

Firstly, it is proposed to perform 3 tests with, and 3 without circulation under different temperature conditions. The cold water temperature ϑ_{PWC} and set point temperature of the DHW module $T_{DHWM,Set}$ are fixed to 10 and 60 °C respectively. The heat source, or primary inlet temperature is varied between 65, 70 and 90 °C, representing a heat pump, gas fired boiler and solar thermal system respectively. The size of the tapping profile that is used varies according to the maximum withdrawal capacity of the DHW module, which varies in relation to the operational temperature conditions.

- Circulation

Up until now, circulation has not yet been considered in existing test procedures. However, circulation can heavily interfere with the secondary outlet temperature due to the rapid change and high interval of the secondary inlet temperature (between 10 and 55 °C). On the other hand, a higher flow rate at the secondary side causes a smaller dead time. Some controllers even regulate the speed of the circulation pump depending on the return temperature, which can cause a drifting inlet temperature at the same flow rate at the tap. Multiple control strategies of circulation pump are used in systems with DHW modules and will cause different effects on the results of the test procedure.

The thermal losses during circulation mode should be defined according to the size of the module. The reason for this is that it will be used in larger systems, which induces greater thermal losses. A proposal is given in Table 2. The pressure losses of the

Table 2: Proposal for the thermal losses according to the size of the module

DHW module	**DN 15**	**DN 20**	**DN 25**	**DN 32**
Circulation losses / W	500	1000	2000	5000

circulation pipes should be negligible, making the pressure losses of check valve and DHWM dominant.

3.2. Pipe damping and admixture

The pipe damping is calculated using the mathematical pipe model (Type 604), where the pipe parameters between the DHW module and the tap can be standardized.

For every disturbance, the consecutive 60 s period of measured flow rate and outlet temperature of the DHW module are fed into the pipe model separately. Fig. 11 shows the effect of pipe damping for such a disturbance for different pipe parameters. On the left the length is varied, and on the right the diameter. Both parameters damp and elongate the recorded temperature fluctuation.

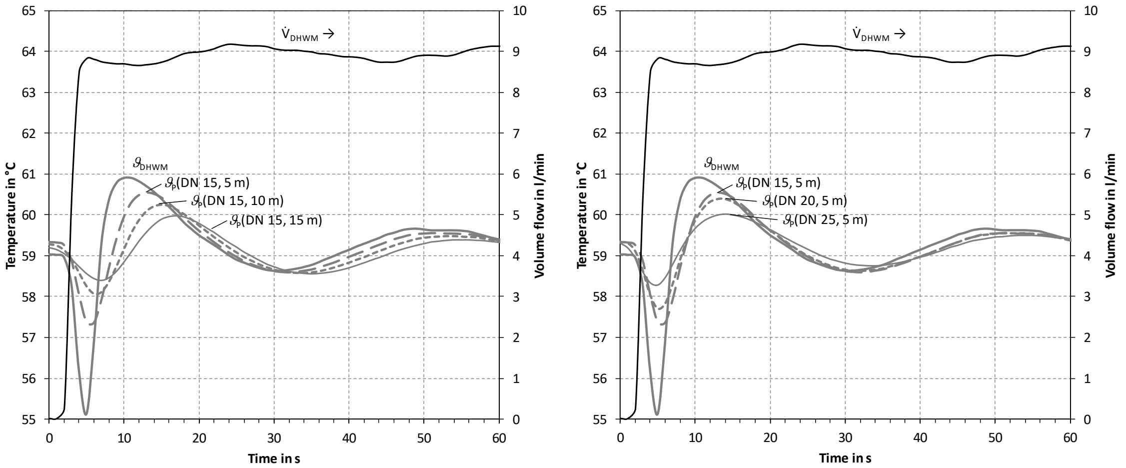

Fig. 11: Damping of the temperature fluctuation after a tapping event with a mathematical pipe model with varying pipe length (left) and varying pipe diameter (right)

Table 3: Proposal for the pipe parameters between DHWM and tap

DHW module	DN 15	DN 20	DN 25	DN 32
Copper / mm x mm	18 x 1	22 x 1	28 x 1.5	35 x 1.5
Length / m	5	10	15	20

Table 3 shows the suggested values for the pipe parameters representing a shower close by (worse case) depending on the size of the module.

According to Eq. 6, the fluctuation leaving the pipe ϑ_P with approximately 60 °C is additionally damped and reduced to approx. 42 °C by admixture of cold water ϑ_{PWC} at the tap ϑ_{Tap} (see Fig. 12).

Every single event (flow disturbance) is then assessed separately regarding comfort criteria (see chapter 3.3).

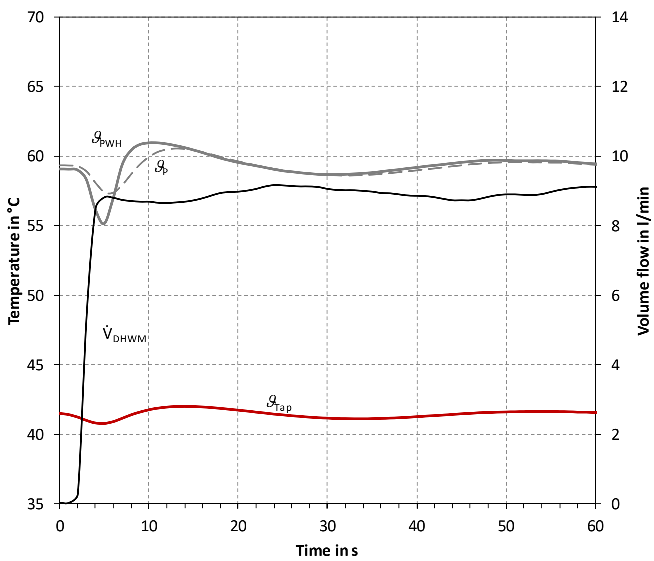

Fig. 12: The method for damping the outlet temperature of the DHW module with a mathematical pipe model and admixture

3.3. Comfort criteria

In general, thermal comfort appears to refer to the subjective state of the observer. The state in which the observer finds itself can often be described in terms of verbal scales for dis(comfort): comfortable – slightly uncomfortable – uncomfortable – very uncomfortable. These verbal scales can in turn be related to certain (dis)comfort boundaries.

The complexity of the transient comfort assessment comes from the uncertainties when relating the subjective psychological basis of thermal comfort to measured temperature fluctuations. The comfortable temperature at which showers are taken differs between human. It is depending on many parameters like gender, ambient temperature, habit, flow rate, and showerhead. Literature on this topic shows that thermoreceptors of human skin sense temperature fluctuations both proportional to the magnitude and due to the rates of change (Lang and Lang, 2007). Thermoreceptors overshoot in case of a stepwise temperature change (Fiala, 1998).

Table 4: Proposal for absolute and derivative thresholds

Absolute thresholds	
B	> 1 K
C	> 2.5 K
D	> 5 K
Derivative thresholds	
B	+/- 0.17 K/s
C	+/- 0.40 K/s
D	+/- 0.83 K/s

(Herrmann et al., 1994) carried out experiments with 30 male test persons with very slow changes of water temperature (0.016 K/s). The persons recognized the change after about ±0.7 K and felt uncomfortable at about ±2.4 K. The threshold for perception reduces approx. by a factor of 2 from ±0.7 K to ±0.4 K with faster fluctuations (0.1 K/s). (Kenshalo et al., 1968) report similar results even for higher rates. Unfortunately, there is no corresponding threshold for discomfort with higher rates. For the time being, the boundaries for absolute deviation are defined with respect to the rate of temperature change based on existing research (see Fig. 13). In the future, experiments should be carried out to map the boundaries of the combination of proportional and rate-related thresholds more precisely.

A proposal for these thresholds is depicted in Table 4. Where the labels relate to the verbal (dis)comfort scale (e.g. D means very uncomfortable etc.)

Evidence shows that the absolute and derivative factors are directly influencing each other. This means that as the rate of change gets smaller, a greater absolute deviation from the set point is tolerated before hitting a certain comfort boundary and vice-versa. This is depicted by the spider web in Fig. 13 assuming linearity for simplicity.

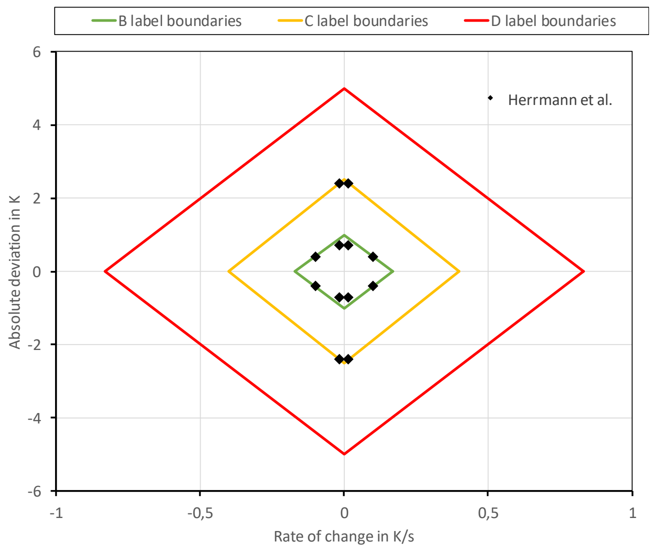

Fig. 13: Relationship between the absolute deviation (dis)comfort boundaries and rate of change compared with literature thresholds

The harmful impact of an excessive temperature depends on its height and its exposure time. (Viola, 2002) shows that water with a temperature of 60 °C causes a first-degree burn after 3 s, whereas water at 55 °C burns the skin after 17 s. The pain threshold for hot water is 45 °C and for cold water is 15 °C (see (ASHRAE, 2001)). Hot water with 45 °C unfolds its harmful effect after more than 2 hours, but it is dangerous anyway if the person tries to move away quickly and falls. Exceeding a temperature threshold of e.g. 50 °C may be punished by a comfort index of this event by 0 %.

These three thresholds (absolute temperature, absolute deviation and rate of change) are used to assess the tapping event from Fig. 11 and Fig. 12. Fig. 14 shows the influence of pipe length and pipe diameter on its comfort index after Eq. 1. As the temperature damping increases with pipe length and pipe diameter the comfort increases with both parameters. It increases not linear as the comfort criteria are discrete. Small changes of temperature deviation or rate of change can lead to a big change in comfort index.

4. Discussion

The extent to which the standardized test procedures can be normalized is highly influenced by the precision with which a given tapping profile is emulated on a DHW module. The speed ($d\dot{V}/dt$) with which the volume flow rate jumps between the different tapping events has a direct effect on the temperature progression at the secondary outlet ϑ_{DHWM}, and will therefore influence the comfort, energy efficiency and capacity assessment results. During this research the lab tests have been conducted using a PID controlled valve. The step between different volume flow rates has been qualified as satisfactory if minimum to no overshoot, as well as a maximum deviation of 0.5 l/min from the required volume flow rate during the tapping event was observed. In continuation of this research a clear outline for the normalization of the tapping profile execution must be presented.

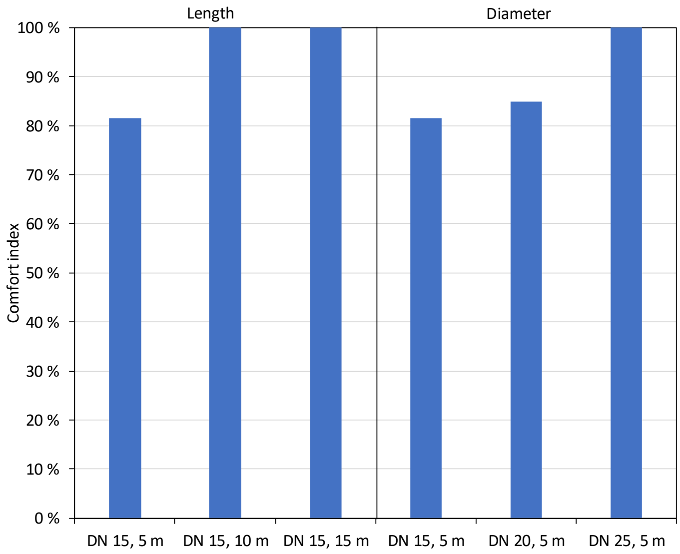

Fig. 14: Influence of pipe length and pipe diameter on comfort index of a single tapping event

Even though the current comfort assessment presents a more rigorous approach to the implementation of thermal comfort and thermal sensitivity, little literature is available regarding the comfort thresholds. In continuation of this research, it is proposed to conduct experiments by exposing test subject to transient showering conditions in order to define the appropriate comfort estimates.

Another key element of the comfort assessment is the effect of the pipe model, used to damp the temperature progression between the secondary outlet of the DHW module ϑ_{DHWM} and tap ϑ_P. Even though the pipe model is successfully validated, it is crucial that the pipe model will again be validated by ISFH with actual measurement data. It is uncertain to which extend pipe damping effects the shape of the temperature progression, which could lead to considerable effects on the results of the comfort index.

Instead of keeping the pipe parameters fix it could make sense to present the comfort index results for several distances between the DHW module and the tap. In continuation of this research, it must be considered if giving multiple comfort indexes weighs up to the simplicity of showing only a single comfort index.

5. Conclusion

As DHW modules contain only small amounts of stagnant potable hot water, which is exchanged very often, they offer the possibility to deliver hygienic potable hot water and to save energy due to lower temperatures. The assessment of DHW module properties is key in building user acceptance, as this is necessary for the dissemination of DHW modules.

This paper presents the state of the art regarding the different assessment properties of the DHW module. Focusing mainly on the comfort property under transient conditions. In addition to this, this paper presents a proposal for a new test procedure for the comfort assessment based on the criticisms of the state of the art that also allows for further standardization. The assessment uses a mathematical pipe model, to damp the temperature progression between the outlet of the DHW module and the tap. Each individual tapping event is assessed by means of comfort criteria regarding the absolute and derivative thermal judgements and are graphically represented in terms of bar charts. It is proposed to use the fraction of the first 60 seconds after a tapping event that is described as "*comfortable*" as a comfort figure.

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