Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Influence of specific characteristics of subjects and environmental conditions on comfort level during showering

To cite this article: K Albrecht *et al* 2023 *J. Phys.: Conf. Ser.* **2600** 092014

Influence of specific characteristics of subjects and environmental conditions on comfort level during showering

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Abstract. In systems that do not store domestic hot water (DHW), temperature fluctuations occur in the hot water temperature at the outlet when the DHW load changes. If these temperature fluctuations arrive at the tapping point, they influence the users' perception of comfort. Especially in the shower these temperature fluctuations can lead to a loss of comfort. Unlike in the field of air conditioning, there have been relatively few studies on the perception of comfort in the shower, and these used only males as test subjects. Therefore, we started a study with 120 persons with the aim to involve a representative variety of test subjects. In our test facility a temperature profile with varying rates of change was imprinted and the test subjects provided feedback on whether they noticed temperature changes or found them uncomfortable. In this study, results on the comfort perception of the participants in the shower are examined in relation to individual factors such as gender, age or Body-Mass-Index (BMI), and the outside temperature. We cannot determine a specific impact of these factors on the comfort perception of a group of test subjects. Neither was an influence on the desired temperatures, which ranged between 33 °C and 45 °C, detected.

1. Introduction

In order to achieve greenhouse gas neutrality in 2045, a 65 % reduction in greenhouse gases should be achieved in Germany by 2030 compared to 1990 [1]. Higher energy efficiency is essential for achieving the climate targets. Conventional water heaters usually consist of a conventional fuel-fired heat generator and a storage tank for domestic hot water (DHW). Via this storage tank, DHW is provided for the building and tempered to 60 °C according to hygienic requirements. This prevents the growth of legionella bacteria. These requirements necessitate high outlet temperatures and circulation return temperatures, which have a negative impact on the efficiency of heat pumps and solar thermal systems and counteract their economic use. By switching to a central instantaneous water heater (IWH) and a buffer tank, the need to heat the entire tank to 60 °C is avoided. Keuler et al. show that this conversion allows the heat generation systems to be optimized for the use of renewable energy [2]. One market barrier to the implementation of energy-efficient IWH systems is the fulfilment of thermal comfort requirements. Since IWH comprise almost no DHW, temperature fluctuations occur when the required load changes. These fluctuations can be minimized by a good control of the IWH but not completely prevented due to thermal capacitive effects. In order to investigate the influence of temperature fluctuations on comfort during showering, an experimental test facility was set up at ISFH. The series of tests can be used to determine when temperature fluctuations are noticed and when they are perceived as disturbing. More than 100 test subjects took a shower and evaluated temperature fluctuations. The test subjects also completed a questionnaire, which makes it possible to perform the evaluation depending on factors such as age, gender, outside temperature or Body-Mass-Index (BMI) and to investigate influences on the perception of comfort during showering.

2. State of the art

There are many investigations focussing on human comfort of air conditioning, but only a few with the focus on comfort during showering. We distinguish two aspects of comfort. First, the desired temperature in steady-state and second the perception of temperature fluctuations. In 1994, a study of Herrmann et al. on thermal comfort during showering was published [3]. The comfort conditions during showering are restricted to thermal comfort, which is why only changes in water temperature, like temperature ramps, are investigated. After a preliminary study with 99 test subjects, female test subjects were excluded because they were too sensitive to the existing pressure variations. Subsequently, comfort was investigated using 30 male test subjects. The results of the study show that sensitivity to temperature changes during showering is slightly different for positive and negative deviations. On average, 34.9 °C was reported as neutral temperature and 36.4 °C as comfort temperature. The conclusions of the study state that humans are more sensitive to a drop in temperature and sudden temperature changes. Deviations from the desired temperature of ± 2.4 °C are classified as uncomfortable [3]. Within a research project for the development of a test procedure for IWH from 2011, comfort level criteria for significant temperature fluctuations during showering are defined. Four comfort levels are classified, which are based on the existing standards on requirements for drinking water heating systems [4]. The European Standard DIN EN 13203-1 and the German Guideline VDI 6003 specify comfort levels based on tolerable temperature fluctuations at the tapping point. Mainly, the classification is used for the design of systems with gas appliances [5, 6].

3. Test facility and procedure

The shower cabin is set up in a climatic chamber, which can be air-conditioned and thus enables reproducible initial conditions of the environment. The room temperature at the beginning of each experiment is between 23 °C and 25 °C. The humidity lies between 50 % and 70 %. The variability within these ranges has no influence on the test results. The exact setting of these factors as well as air conditioning during the experiment is not possible. The climatic chamber with the shower cabin is shown in Figure 1.

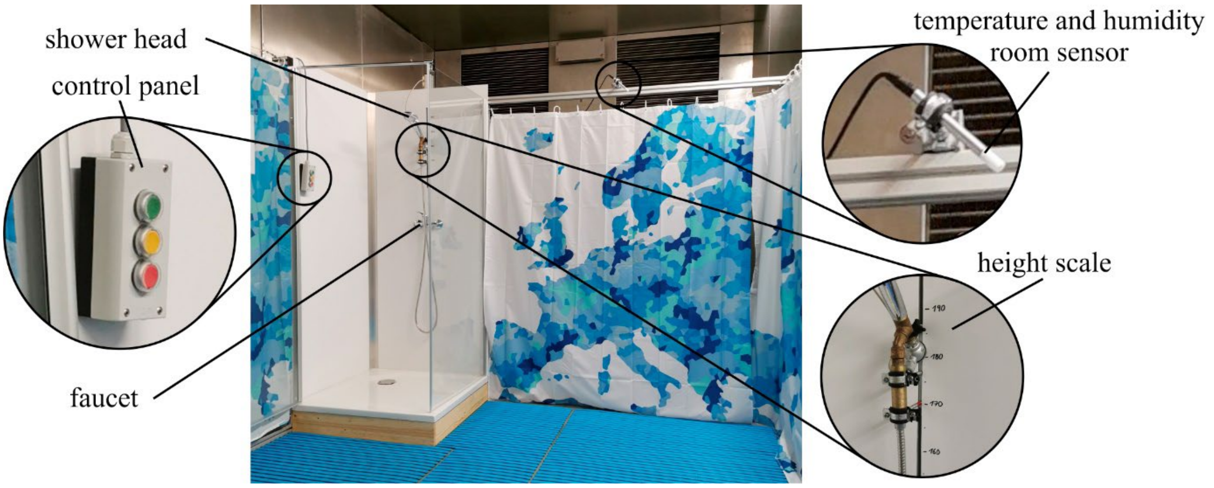

Figure 1. Shower in the climatic chamber

The shower is equipped with a one-hand mixer tap, which allows the test subject to adjust the water temperature and flow rate. On the left there is a moveable control panel with three different buttons to provide feedback. The green button is to start the test sequence, the yellow button implies the perception of the fluctuation, while the red button stands for discomfort and interrupts the fluctuation. The height of the shower head is adjusted according to the size of the test subject to ensure that the distance between the shower head and the back is approximately the same for each test (30 cm). The flow rate is dictated by turning the faucet on completely and is approximately 11.5 ± 0.5 l/min for each experiment. There is a rapid temperature sensor in the shower head, which is used to measure the tap temperature. The temperature difference between the tap temperature and the water temperature on the skin is considered in the evaluation by determining a delay time of 1 s in total. The tap temperature is therefore taken as the reference value for the test subject's comfort rating. A storage system at 60 °C is used for the DHW supply and an auxiliary heater in the potable cold water imprints the temperature fluctuation in 2 rounds of experiments. In the first test round, the tap temperature fluctuation is caused by an electric heating rod. For the second round of experiments, the temperature fluctuations are realized by an additional heat exchanger, since this allows higher rates of change of the tap temperature. Coriolis sensors with an accuracy of ± 0.1 % are used for mass flow measurement. Rapid PT100 class A sensors are used for temperature measurements. The temperature sensors were checked and calibrated at ISFH before use. The measurement data as well as the feedback signal are recorded and logged every second during the experiment. The temperature fluctuations are pre-programmed as a defined sequence of positive and negative temperature deviations. Here, the initial temperature corresponds to the desired temperature set by the test subject. In the first test round R1, the influences due to the order of the temperature fluctuations are additionally investigated. For this purpose, the events are arranged differently with respect to the direction of the temperature change and the rate of change. Table 3 shows three different programs which are randomly assigned to the test subjects. In the second round R2, one optimized program is used.

Table 1. Composition of programs

Program	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7
R1 A	R1hot1	R1hot3	R1cold3	R1cold3	R1cold2	R1hot2	R1cold1
R1 B	R1hot1	R1cold2	R1cold3	R1hot2	R1cold3	R1hot3	R1cold1
R1 C	R1hot1	R1cold3	R1hot3	R1cold3	R1cold2	R1hot2	R1cold1

Figure 2 shows examples of temperature profiles for both rounds. The water temperature at the shower head is plotted on the Y-axis in °C and the time in s on the X-axis.

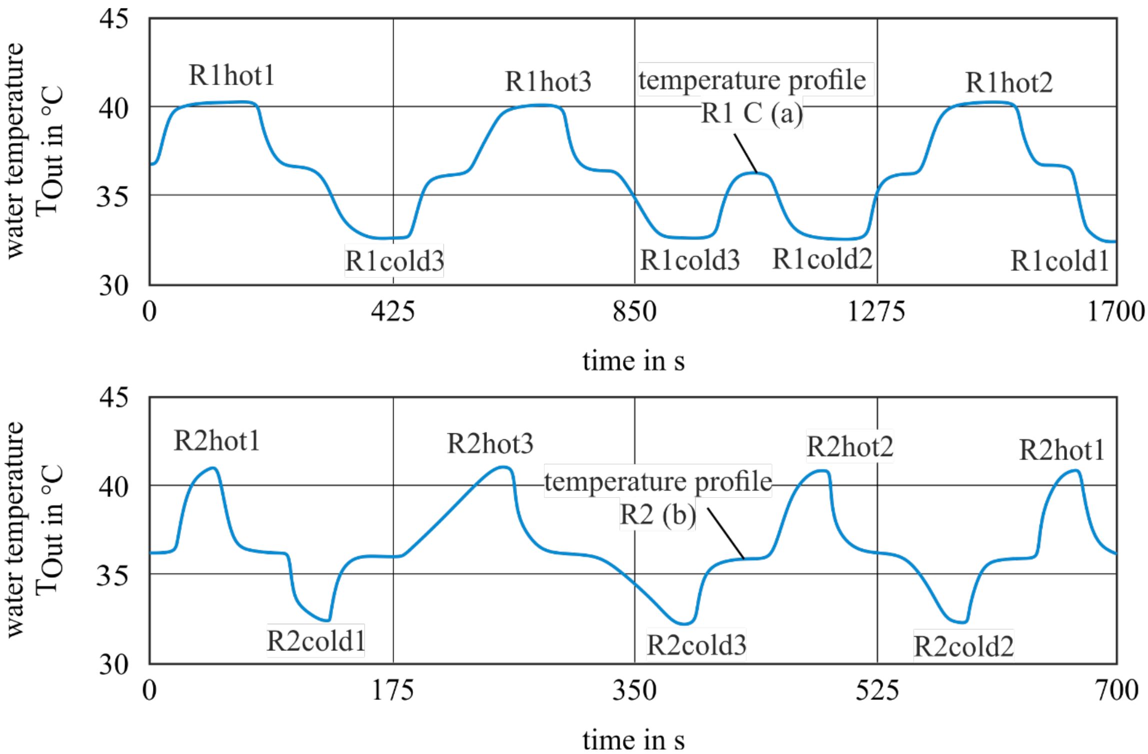

Figure 2. Temperature profiles of round R1 C (a) and round R2 (b)

The programs are built up from the different events with pauses in between. The desired temperature is present during the pauses. At the beginning of the experiment, the test subject fills out a questionnaire. Physical characteristics such as age, gender, height and weight are queried. External factors such as weather and outside temperature are also documented. A detailed briefing of the test subject follows in order to minimize errors in the execution of the experiment. The test subject enters the climatic chamber. The test subject first adjusts the height of the shower head and then sets the personal desired temperature at the maximum possible volume flow. After a confirmation with the green button the automated test procedure starts and the test subject evaluates the recognized temperature changes. The yellow button is defined as a signal for "I feel a change in water temperature", which is a marker for the detection of temperature fluctuations. The red button should be pressed when the subject feels discomfort. The interpretation of discomfort is a particularly subjective assessment and is different for each person. Additional descriptions during the instruction should provide an interpretation as clear as possible. The tests last between 10 and 30 minutes.

4. Results

In the following, the results regarding the different influencing factors are presented. Both rounds of the test series are combined, since the structure of the different programs has no effect on the results. The correlations to the perception of comfort and to the chosen desired temperature are investigated. A reproducibility of a subject's response was investigated by repeating the experiment on different days. There is a deviation of the comfort range of ± 0.21 K over all events of the experiment. Since this deviation is negligible, the reproducibility can be confirmed. First, the influence of the outside temperature (season) on the desired temperature is considered. The outside temperature was documented in both rounds at the beginning of the test. Figure 3 shows the desired temperature as a function of the outside temperature. In general, a high dispersion of the desired temperature between 33,2 °C and 44,0 °C can be observed. The mean desired temperature is 38.6 °C, with the middle 50 % of subjects choosing a range between 36.9 °C and 40.4 °C. The outdoor temperatures range between 1 °C and 26 °C, which is due to the different time periods of the execution of both rounds. Round 1 was carried out in winter, while the experiments in the second round took place in summer. There is no discernible correlation between the desired temperature and the outdoor temperature in the context of this series of experiments and corresponds with the results of Wong et al. [7].

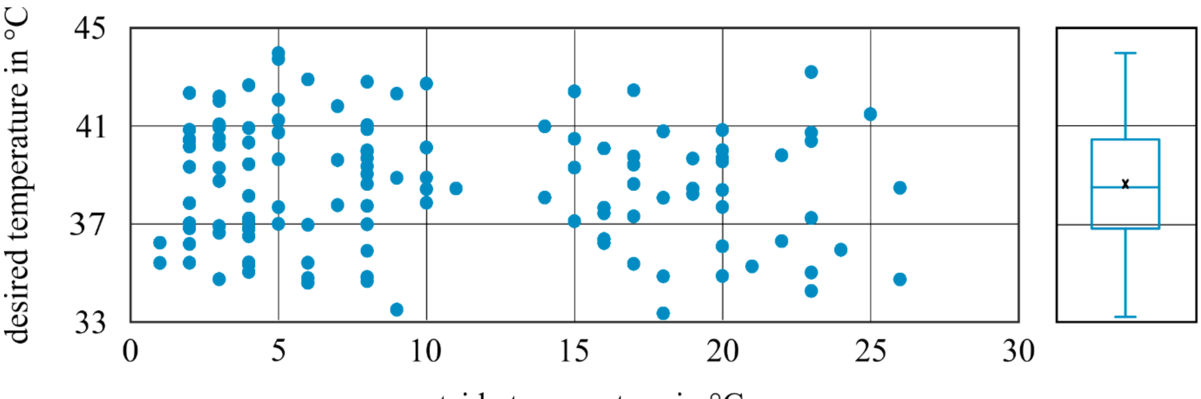

Figure 3. desired temperature as a function of outside temperature and box plot of desired temperature

One possible reason for this observation may be the acclimatization of the test subject during the preparation time. The test subjects were in an air-conditioned building about 10 to 15 minutes before the start of the experiment. When evaluating the yellow and red button presses, no correlation of the outside temperature to the perception of comfort or to the detection of the temperature fluctuations could be found either. According to the questionnaire data, two thirds of the test subjects were male and one third female. The influence of gender on showering comfort will be examined in more detail below. Figure 4 shows the desired temperature and temperature difference to desired temperature, when the red button is pressed (discomfort), as a function of gender. The data shows no dependency between the preferred shower temperature and gender. A large scattering of data points is also evident here. The perception of discomfort is also independent of gender. Figure 5 shows the dependence between the gender of the test subject and the perception of a temperature fluctuation. There is no correlation between the detection of a temperature change and the gender of the test subject. However, there is a slight negative correlation in Figure 5 that may indicate that persons preferring hot showers are more sensitive to hot events, and vice versa.

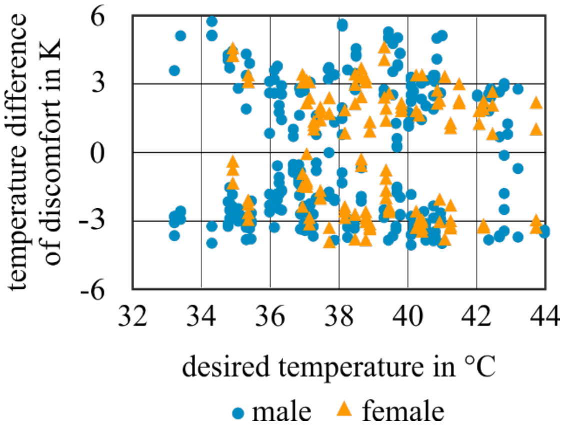

Figure 4. temperature difference of discomfort as a function of desired temperature and gender

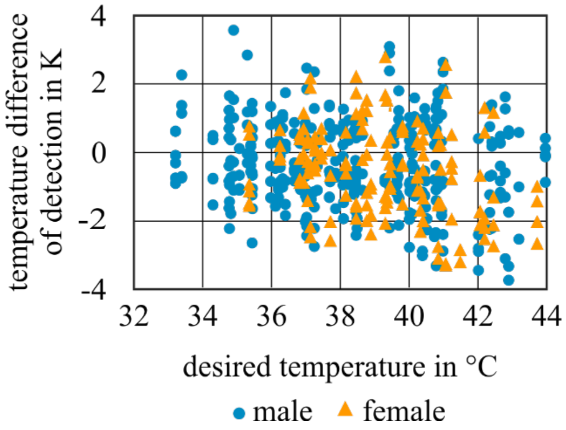

Figure 5. temperature difference of detection as a function of desired temperature and gender

Another biological factor to be investigated is the influence of the subject's age. For the presentation of the results in Figure 6, the data were grouped into three age categories. Test subjects under 35 years are represented by dots, test subjects between 35 and 55 years are marked by triangles, and those over 55 years are marked by squares. Due to the small sample size of the over 55-year-olds, the data are less significant than those of the other two age groups.

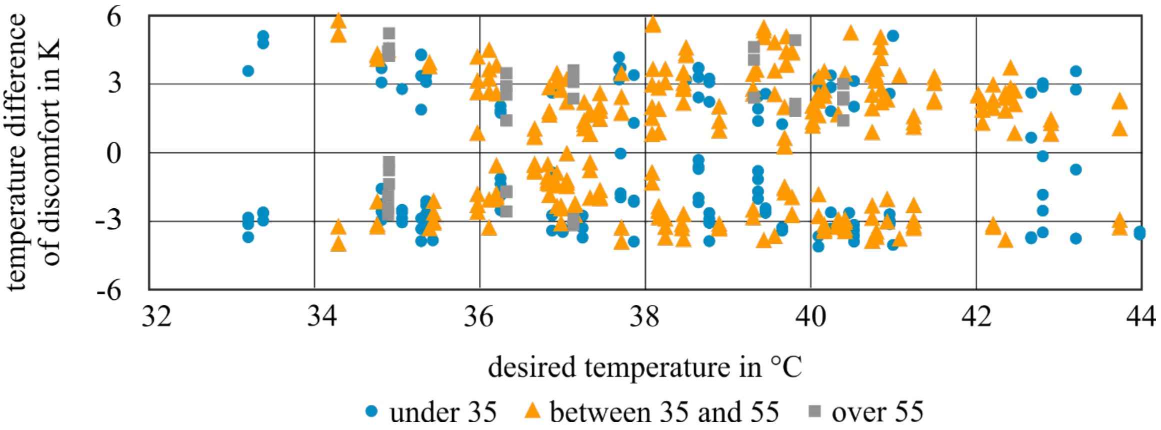

Figure 6. temperature difference of discomfort as a function of desired temperature and age

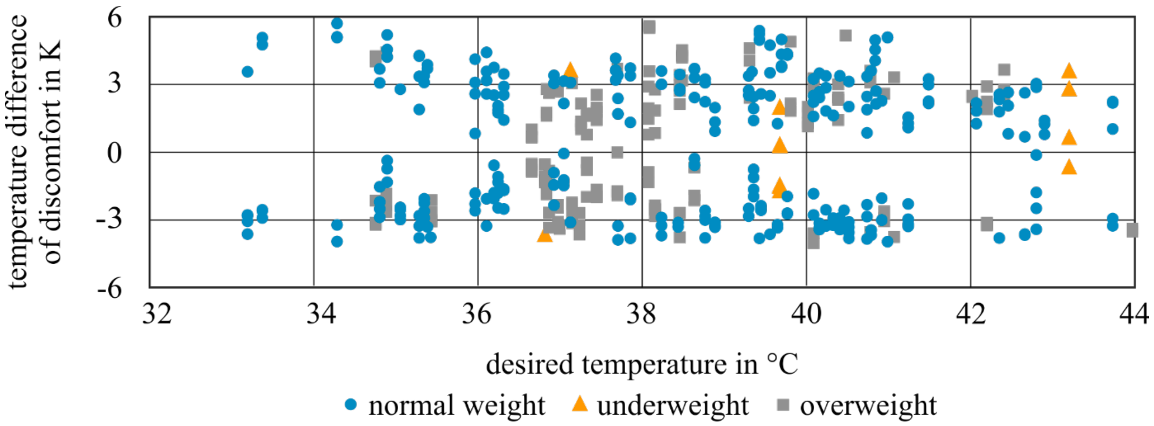

Figure 7. temperature difference of discomfort as a function of desired temperature and BMI

Due to the arbitrary distribution of the data points, a dependence between comfort perception and age of the test subject can be excluded. Neither a correlation to the choice of the desired temperature nor a correlation to the detection of temperature fluctuations can be found. In the following, the BMI of the test subjects is considered. This is calculated from the queried height and weight. Figure 7 shows the comfort limit as a function of the desired temperature. A strong scattering of the data can be seen, which shows that the factors are independent. A correlation to the desired temperature cannot be determined either.

5. Summary

Energy consumption in the heating sector can be reduced by systems with a central buffer tank. When DHW is heated according to demand, temperature fluctuations occur that reduce comfort at the tapping point. In this paper, the influence of various factors on the perception of discomfort during showering was investigated. In addition to biological characteristics of the test subject, such as gender, age and BMI, the outdoor temperature was also considered as an influencing factor. The experiments showed that the perception of comfort is not significantly related to the factors mentioned. The range of desired temperature is very wide, from 33 °C to 45 °C (mean 38,6 °C). In comparison, Herrmann et al reported a mean comfort temperature of 36.4 °C, which does not reflect this wide range of desired temperatures. Previous data, as well as the data from this study, can serve as a meaningful basis for comfort studies. With the available data, different comfort levels could be classified and apply to a large part of society without a dependency of personal characteristics. In order to develop assessment methods with comfort levels, further results regarding temperature differences for perception and discomfort will be derived. Other criteria, such as the rate of change, can also be examined in more detail to verify the results of former studies.

Acknowledgment

The presented work is part of the research project “TA-DTE-XL” (grand no. 03EN1025A) a joint project of ISFH and Viega GmbH & Co. KG. The authors are grateful for the support of the State of Lower Saxony and the Federal Ministry for Economic Affairs and Climate Action (BMWK). The authors are responsible for the content and would also like to thank PAW GmbH & Co. KG, Oventrop GmbH & Co. KG, Solvis GmbH, Malotech GmbH, cbb software GmbH, Taconova GmbH, Reich + Hölscher, Varmeco GmbH & Co.KG, Bosch Solarthermie GmbH, Vaillant GmbH for their support.

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