Fluctuating temperature of the mains water throughout the year and its influence on the consumption of energy for the purposes of DHW preparation

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Abstract. The article discusses the influence of the cold water temperature on the amount of energy consumed for the purposes of the DHW preparation in multi-family buildings. The article begins with a presentation of the DHW consumption readings from a multi-family building, recorded on a monthly basis during the period of 4 years. The readings constituted the base for calculating the demand for energy for the purposes of the DHW preparation. Subsequently, basing on the output water temperature readings from the water treatment plant, it was proved that the temperature of the mains water fluctuates throughout the year. The review of the available literature, as well as the measurements, confirmed that it is necessary to develop a new model of the cold water temperature that would take into account the type of intake in a water treatment plant. The final part of the article presents how the accepted assumptions about the temperature of the mains water influence the consumption of energy for the purposes of the DHW preparation.

1 Introduction

With the development of more efficient heat insulation dedicated for residential buildings, the share of energy fed into the DHW preparation system has become increasingly important. The fact that the procedures of estimating the energy demand are oversimplified is more and more evident. The shortcomings of these procedures may lead to significant imprecisions when developing systems and creating energy analyses. One of the main factors influencing the consumption of energy for the purposes of the DHW preparation is the cold water temperature, treated in energetic analyses as a value remaining constant throughout the year. The authors of the EN 15316-3-1 [1] standard, though, have made themselves very clear. They said that in the case of more precise approach to analyses of the energy demand one should take into account the fluctuation in the cold water temperature throughout the year, as it has a great impact on energy consumption. They have also underlined that the temperature of cold water depends on location, a fact which should

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be included in the domestic appendix to the standard. This creates a need to review existing models of water temperature at the input in the hot water preparation system. The author has also used a real building as an example of how the accepted assumptions influence the modelling of the demand for the energy for the purposes of the DHW preparation.

2 Models of cold water temperature

Despite the influence of seasonal fluctuation in the cold water temperature, underlined in the standard [1], on the consumption of energy for the purposes of DHW preparation, the authors of the Nov 6th 2008 Order of the Ministry of Infrastructure and Development on the Methodology of Determining the Energy Pattern of a Building insist that, for the purpose of calculations, one should assume that the cold water temperature equals 10°C [2], although they did not specify what conditions may influence the temperature. Scientific publications that have been devoted to this subject justify the belief that the cold water temperature fluctuates throughout the year. Results presented in the articles [3–5] have shown that fluctuation in the temperature of the mains water is related to the outdoor temperature, which is also subject to fluctuation. To test the influence of the temperature of the mains water on how prone the supply network was to failure, Kwietniewski, Miszta-Kruk and Piotrowska [3] used data obtained at the Warsaw supply network. The measurements were obtained from 20 stations installed in the network. Analysing the average daily temperature one can notice that the mains water at the output of the water treatment plant in winter 2006 - 2007 had a temperature of 2-3°C, whereas at the turn of July and August its temperature was as high as 25°C. Dąbrowski [4] investigated the influence the fluctuating temperature of the mains water on the carbonate balance. The measurements were obtained from 90 measuring stations installed in the network and at the output of the water treatment plant. The temperature of the mains water fluctuated between 3.8°C and 20.6°C. The author, knowing the temperature of water at the output of the water treatment plant, has also investigated the influence of the ground temperature on the temperature of the mains water. The biggest cooling factor was observed in June (-1,8°C), whereas the biggest heating was recorded in December (1,9°C). In both cases the major part of the year is characterized by a temperature much higher than 10°C when it comes to values recorded at the output of the water treatment plant, as well as in more distant points of the network. In his analyses of the consumption of heat used for the purposes of the DHW preparation, Bartnicki and Syposz [5] presented a diagram representing the temperature of the mains water for two localisations in Wrocław. According to the authors, the difference in temperatures can be explained by the fact that the measurements were taken in two places in the city. At the same time they proved that the average cold water temperature in both places was around 12°C.

Models available in foreign literature devoted to the subject in hand very often describe the temperature of the mains water as dependent on the outdoor temperature. An example of such a model was presented by Burch and Christensen in the National Renewable Energy Laboratory [6]. The authors have formulated an equation reflecting the correlation between the outdoor temperature and the temperature of the mains water. To describe the independent variable the authors have used the sine function where the average temperature of water varies in direct proportion to the annual average outdoor temperature. In the model the author used the displacement constant T, whereas the ratio R and the parameter ϕ have been presented in the linear function in relation to the average outdoor temperature. This relation has also been used in the Building America Research Benchmark Definition [7]. The authors have formulated an equation which reflects the correlation between the outdoor temperature and the temperature of the mains water. The coefficients in the equation were corrected on the basis of the measurements taken by Abrams and Shedd [8], FSEC [9] and Sandia National Laboratories [10].

Another series of experiments was conducted in Hong Kong during one week in January, February, July and October. The experiments were related to the recovery of heat from showers and they indicated a close relationship between the outdoor temperature of water and the temperature of water fed into the DHW preparation system [11]. The correlation ratio between the two analysed temperatures was 0.97.

Fisher, Wolf et al. [12] have presented another model. The authors, on the basis of assumptions outlined in Task 44 [13], have assumed that the temperature of the mains water depends on the average annual outdoor temperature. The equation formulated by the authors was based on a model of ground temperature from [14], at the same time taking into account the seasonal fluctuation in the cold water temperature as described in [15]. The shift of the presented function is related to the coldest day of the year.

The authors of Residential ACM Reference Manual [16] assume that the fluctuation in the cold water temperature should be analysed in a daily time frame, but not more frequently. Apart from the influence of the outdoor temperature, the temperature of cold water is also influenced by the ground temperature measured over the course of the last 31 days.

In their analyses the authors of the publication [17] used measurements recorded in the Netherlands. They concluded that the temperature of the mains water at the receiver's might equal to the temperature of the ground surrounding the supply network at the depth of 1 m. It is so, because the time when this part of the network is heated is usually shorter than the time the water spends in it. The sunlight and the daily fluctuation in the outdoor temperature have no significant influence on the ground temperature below the depth of 200mm, where the supply network runs. Whereas in [18] the author, by measuring the ground temperature, has confirmed that in Africa, the temperature of water fed into the DHW preparation system, transmitted at the depth of 300mm, equalled to that of the ground.

Publications on the discussed subject have also included actual measurements of the temperature of the mains water. One of such is a publication [19], including a profile of energy consumption based on the electric power consumption measured in 204 residences in Central Florida. The author has proved that the demand for electric power used in DHW preparation is subject to seasonal fluctuations. The fluctuating demand for power can be a result of the fluctuating temperature of the mains water. The difference in temperature between January and August is around 8°C. The highest temperature of water in the network was recorded in August, when it reached 27.2°C, whereas the lowest temperature was recorded in January and it was 19.4°C. The annual average temperature of water at the input to the DHW preparation system was 24.2°C.

Analyses of the consumption of energy used for the purposes of DHW preparation were also included in the publication [20]. The authors have simulated the energy consumption in three referential buildings: an office block, a residential building and a three-star hotel, all located in Senegal. They have also taken into account the influence of the building's location on the energy consumption. In order to run their simulation they used, among others, the data from the National Meteorology and local water supply companies. The data concerned the fluctuation in the temperature of the mains water.

The authors of the Solar City [21] test had all the data about the temperature of water fed into the DHW preparation system as well as the temperature of cold water fed into potable water delivery points in 119 households. The authors of the test, apart from the sinusoidal nature of the fluctuation in the temperature of the mains water delayed by a month in relation to the outdoor temperature, have noticed the problem of an increasing temperature of cold water in rooms at the time of no water demand, which is why they used selected data in their analyses. At the time when water does not flow, its temperature reaches the outdoor temperature, whereas the volume of heated water depends on the volume of the feeding pipe. Moreover, the authors have concluded that water, as its volume in the tank increases, has also an influence on the temperature recorded inside of the feeding pipe.

3 Measurements analysis

3.1. Measurements

The analyses of the energy consumption used for the purposes of DHW preparation, presented in the further part of the article, have been based on an actual hot water consumption recorded in a multi-family building and on the models of cold water temperature outlined in the available literature. The measurements of DHW consumption were taken from a low temperature gas boiler room supplying three multi-family buildings. All the buildings comprised of 130 flats measuring 26 m^2 to 103 m^2. The measurements were recorded every 15 seconds by means of a water meter. The water consumption recorded over a course of a month was calculated as a difference of two values: the meter reading from the beginning and from the end of a given month. The collected data spanned the years from 2012 to 2015 and they were presented on Fig. 1. The actual measurements of the hot water consumption indicate a significant drop in the consumption of water during the summer, a season popular for organizing holidays. This might suggest that it is worth basing analyses on the actual water consumption or using coefficients correcting water consumption in the summer. However, the author of this article has focused to a larger extent on the analysis of the fluctuation in the cold water temperature as well as its influence on the estimations of energy consumption.

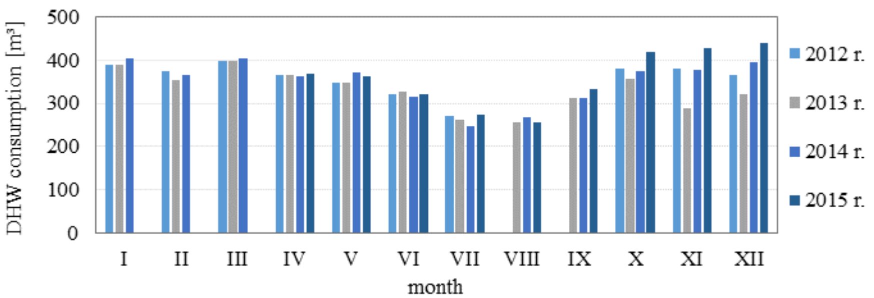

Fig. 1. DHW consumption in multi-family buildings.

Analyses of the energy consumption were preceded by an analysis of the annual fluctuation in the temperature of the mains water. For this purpose the author has used measurements of the temperature of the mains water taken by the Municipal Water and Sewerage Company in Wrocław as well as the models existing in the literature. The measurements of the cold water temperature were taken at the output in the "Mokry Dwór" (U1) and "Na Grobli" (U2) water treatment plants. Fig. 2 represents the fluctuation in the average monthly temperature of the mains water at the output in the water treatment plant between 2011 and 2016. The U1 plant is supplied with water from an underground intake. Fluctuation in the temperature of water throughout the year is much smaller than in the case of a surface intake of the U2 plant, supplying the mentioned multi-family building. The highest average monthly temperature of water at the output in the U1 plant was recorded around November and it was around 14.6°C whereas the lowest average monthly temperature, 8.9°C, was recorded around March. The highest average monthly temperature of water at the output in the U2 plant was recorded around July and it was approximately 22.2°C whereas the lowest average monthly temperature was 1.7°C. As this temperature does not fluctuate throughout a day, the average monthly temperature was calculated on the basis of a series of daily measurements. It is worth remembering that the temperature of water at the receiver's might also be influenced by the temperature of ground around pipes. But works published on the subject indicate that the temperature of ground can change the temperature of water at the receiver's by 2-3°C. Therefore, it cannot cause a significant function flattening and the levelling of the two profiles.

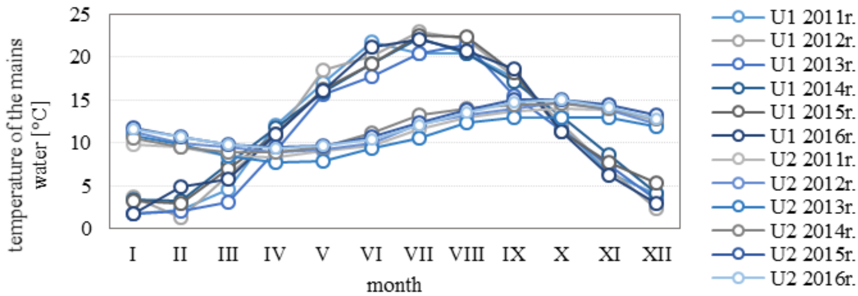

Fig. 2. Fluctuation in cold water temperature in the U1 and U2 water treatment plants.

3.2 Cold water temperature analysis

The analysis of fluctuations in the temperature of the mains water was carried out in particular months of the year. For the purpose of the analysis the author used data related to the temperature of the mains water at the output in the water treatment plant as well as the models of cold water temperature existing in the literature. Fig. 3 represents the existing model of temperature developed in National Renewable Energy Laboratory [6], as well as the models described in AMC [16], TASK44 [13] and in the publication [11]. The model included in TASK44 [13] constituted a relatively successful attempt at describing the temperature of water at the output in the U2 water treatment plant, as the measurements indicated similar values. However, the model reflects a different shift of the function as the maximum temperature was recorded at the turn of July and August, not like in the case of the measurements, where the highest temperature was recorded at the turn of September and November. At the same time, the model included in AMC [16] accurately describes the measurements taken from the surface intake at the U1 water plant, because the measurement differences for both the cases are relatively low. So the values recorded in months indicating the lowest and the highest temperatures overlap with measurements included in the model. Where there are no domestic models of the temperature of the mains water, the authors of the EN 15316-3-1 [1] recommend that the average water temperature of 10ºC should be used throughout the year. This recommendation was applied in the domestic laws on the methodology of determining energy patterns of buildings [2]. Unfortunately, this approach fails to represent the actual fluctuation in the temperature of cold water, which can be concluded on the basis of the presented measurements. The relationship described in [2] does not justify the trends of the fluctuation in the cold water temperature observed in both of the above-mentioned water treatment plants, as it assumed that the temperature of the mains water is never lower than 10ºC.

The recorded measurements have proved that in order to determine the temperature of water at the receiver's it is necessary to take into account the kind of the water intake. Such distinction has not been made in the existing literature concerning the discussed matters.

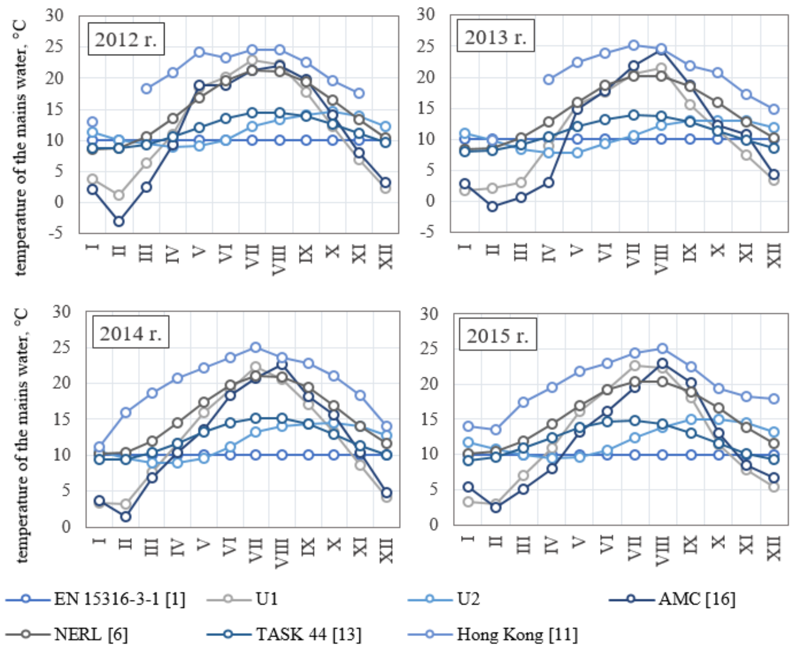

Fig. 3 Fluctuation in cold water temperature in 2012-2015.

3.3. Influence of the temperature of mains water on the consumption of energy for the purposes of domestic hot water preparation

The study presents the difference between the results of simulation of energy demand for the preparation of domestic hot water. For this purpose, the dependence proposed in the European Standard EN 15316-3-1 [1] and presented in Equation 1 was used. The general approach of this standard is based on the calculation of the daily energy demand (Qw,day) basing of the daily consumption of the hot water (V_{DHW}) and the temperature difference between the cold (T_{CW}) and hot (T_{DHW}) water.

$$Q_{DHW} = 4{,}182 \cdot V_{DHW} \cdot (T_{DHW} - T_{CW}),\ kJ/month \qquad (1)$$

For the analysis the author proposed the following five models of the energy demand for the preparation of hot water (described in Table 1). Individual models differ in assumptions about the temperature of the mains water. For this purpose, cold water temperature models available in the literature and shown in Fig. 4 were used. As a reference point the model I of the energy demand was adopted. The model has been developed basing on the measurements of the water consumption in the buildings and the expected cold water temperature described in the European Standard EN 15316-3-1 [1] and included in the Polish regulation RMIiR [2].

The deviations of the monthly energy demand from the values adopted as the reference level for the different models were illustrated in Fig. 4. A significant deviation is apparent for the models where the demand for the hot water is calculated based on the model V, in which the cold water temperature model was developed basing on Hong Kong [11].

Table 1. Assumptions for the calculation of the consumption of energy for the purposes of domestic hot water preparation.

Model	DHW demand, V_{DHW}	Cold water temperature, T_{CW}
I	measurement	EN 15316-3-1 [1] RMIiR [2]
II		AMC [16]
III		NERL [6]
VI		TASK 44 [13]
V		Hong Kong [11]

The AMC [16] model, which best describes the supply water measurements of the multi-family building under analysis, also shows a large deviation of results. In winter, the deviation is + 30% (February 2012), and in summer: -30% (July 2013). A much smaller deviation is obtained using the model from TASK 44 [13]. In winter, this error is + 4%, and in summer: -10% (July 2014, August 2014 and July 2015).

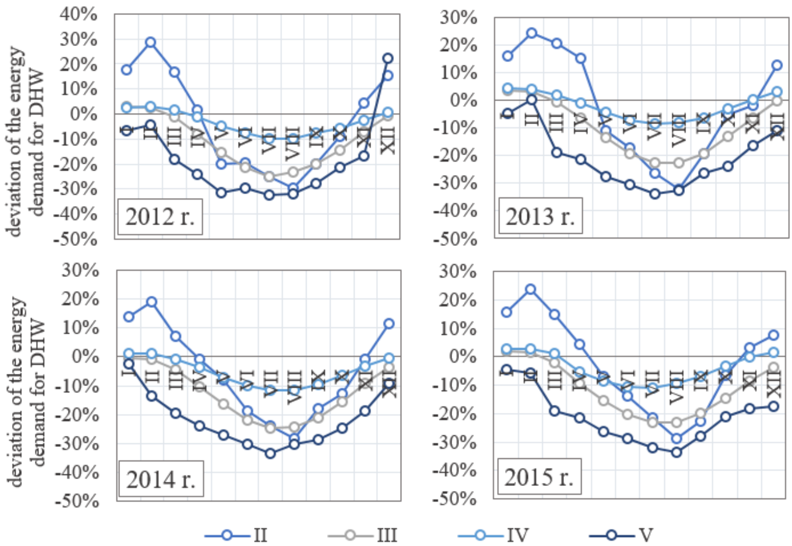

Fig. 4. The deviations of the energy demand for domestic hot water preparation.

4 Conclusions

The energy demand for the domestic hot water preparation is not constant during the year, because it depends both on the consumption of hot water and on cold water temperature at the inlet to the DHW preparation system. The paper shows that the adoption of a constant temperature of the mains water in the calculation leads to large differences in the estimation of energy consumption in relation to the models presented in the literature. It was also shown that the seasonal change in temperature of the mains water is strongly related not only to the temperature of the outside air, but also to the type of intake in a water treatment plant. Adoption of the wrong the type of intake in a water treatment plant can lead to errors in the energy consumption estimation at the level of 20% in summer. The solution for the problem analyzed in the article has already been presented in the dissertation [22]. This article aims at reviewing the existing models and showing the effect of the adopted temperature on the amount of energy used to prepare the hot water.

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