Changes in the heating load of domestic hot water and its impact on the design of the district heating network

TEET-ANDRUS KOIV, ALEKSANDER KOVSHIKOV
Department of Environmental Engineering
Tallinn University of Technology
Ehitajate tee 5, 19086 Tallinn
ESTONIA
Teet.koiv@ttu.ee http://www.ttu.ee

Abstract: - The article gives an overview of the changes in the field of domestic hot water (DHW) consumption. In Eastern Europe instantaneous water heaters are widely used for DHW heating. Over the past 20-25 years there has been a significant change in DHW consumption in Eastern Europe and Estonia. The changes have been so great that new dimensioning methodology is needed. This necessity has also been stated by Dutch investigators. The developed methodology allows to reduce the capacity of instantaneous DHW heaters in residential, educational and public buildings by up to two times. The new calculation methodology of DHW heaters can significantly reduce duct size in tree-shaped district heating (DH) networks, the station power and maintenance costs.

Key-Words: - DHW consumption in residential buildings, DHW heating load in educational buildings, DHW heating load in public buildings, DHW influence on DH system dimensioning

1 Introduction

There have been great changes in DHW (domestic hot water) consumption in the past 20-25 years. In particular, great changes have taken place in Eastern Europe.

Extensive research into DHW consumption has been done in the former Soviet Union. DHW consumption and the consumption profiles in the 1960s and 1970s are presented in articles [1, 2], the latter of which treats the research into DHW consumption and consumption profile conducted by Tallinn University of Technology in apartment buildings in the Mustamäe district of Tallinn in the years 1973–1974.

In Asia, DHW consumption has been studied in quality hotels in Hong Kong [3]. An article by Cheng deals with the studies of DHW consumption in residential buildings in Taiwan and with energy-saving possibilities in relation to heating water [4]. An article by Carrington, Warrington and Yak treats DHW consumption in New Zealand households [5].

In Africa, investigations of DHW consumption have been carried out in the Republic of South Africa. In Johannesburg a year-round study of DHW consumption was conducted, in which the researchers also displayed the hourly consumption [6]. Problems of DHW consumption in South Africa are also dealt with in Vine, Diamond and Szydlowski's article [7] and Rankin and Roussau's article [8]. An article by Meyer gives a survey of DHW consumption in South Africa [9].

In Hungary, Nemethi and Szantho have studied DHW consumption and the consumption profiles in more than 60 residential buildings [10, 11].

One of the few doctoral theses on DHW was written by Savičkas in Lithuania [12]. The thesis comprises the DHW systems of apartment and public buildings, their functioning, DHW consumption, variations in consumption and DHW temperature.

The largest number of investigations in the field of DHW consumption have been done in the US [13, 14].

The year 1998 saw a thorough investigation of DHW consumption in English residential buildings [15]. Its main aim was to gather data on DHW consumption in residential buildings and the habits of their inhabitants. The study showed that the average DHW consumption by washing machines was 4 l per person per day and by showers and hip baths 35 l per person per day, with an additional 10 l/per person per day for hygiene and dishwashing in a sink. In total, DHW consumption was 49 l/per person per day.

From the recent articles, one of the most remarkable articles is by Agudelo-Vera et al about dimensioning the hot water system in hotels [16]. The article states that the current methodology needs improvement. The common practice leads to oversized systems and reduced DHW quality. A new methodology of dimensioning the hot water system is proposed.

2 The DHW systems of buildings

According to where hot water is prepared, DHW systems are divided into:

- central systems
- local systems

Water heating equipment, in turn, is divided into instantaneous water heaters and storage water heaters.

In Eastern Europe central DHW systems with DHW heating in instantaneous water heaters prevail (Fig.1). Storage heaters are also used, in which case, however, Legionella problems may occur.

There have been great changes in domestic hot water (DHW) consumption in the past 20-25 years. In particular, great changes have taken place in Eastern Europe and in Estonia.

In Eastern Europe central DHW systems have been most common (Fig.1) and instantaneous water heaters (Fig. 2) are widely used for DHW heating.

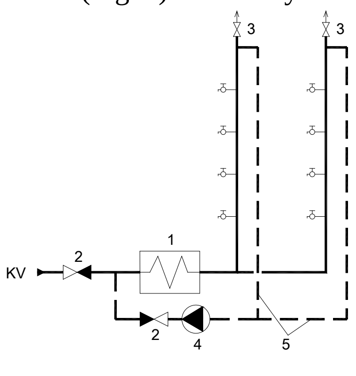

Fig.1. Central domestic hot water system: 1 – instantaneous water heater, 2 – return valve, 3 – air removal device; 4 – circulating pump, 5 – circulation loop.

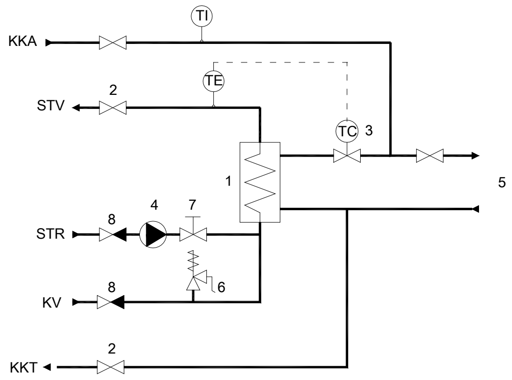

Fig.1. The single-stage instantaneous heat exchanger for DHW heating: 1 – instantaneous water heater, 2 – valves, 3 – temperature controller, 4 – circulation pump; 5 – heat substation connections; 6 – safety valve, 7 – adjusting valve, 8 – non-return valve, KKA – district heating flow line; STV – hot water, STR – hot water circulation, KV – cold water supply; KKT – district heating return pipe

For example, in South Europe, but also in some other countries, local water heaters are usually used.

3 Water consumption in apartment buildings during different years and dimensioning the DHW heating load

The hot water consumption data and changes in them in recent years are of interest. The first more relevant study of hot water consumption of the past decades in Estonia was carried out in the years 1973–1974 [2]. Since the year 1998 hot water consumption in apartment buildings in Estonia has been analyzed continuously by the Chair of Heating and Ventilation of Tallinn University of Technology.

To better understand the water consumption analysis, the results are presented in litres per day per person, as well as in litres per day per 1m² of the total area of the apartment.

The comparison of DHW consumption in apartment buildings in Tallinn in 1974 with the consumption 30 years later is presented in Fig.3. The results are presented in l/m² per day [2].

Table 1 Hot water consumption data in the apartment buildings of the Tallinn District in the years 1973–1974 in litres per person

	Average consumption	Ranges
Monday	83	77-98
Tuesday	81	74-93
Wednesday	81	68-90
Thursday	80	70-88
Friday	90	81-107
Saturday	123	112-144
Sunday	125	111-150
Average	95	85-110

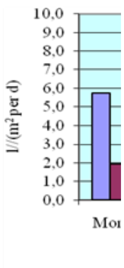

Fig. 3. Average DHW consumption per weekday and per week in the years 1974–2004

The extent of hot water consumption in different apartment buildings in the years 1999–2004 is presented in Fig. 4. As the results show, the average hot water consumption was 60 litres per day per person in 1999 and decreased by up to 44 litres per day per person in 2004, i.e. by more than a quarter. The top consumption data have also decreased.

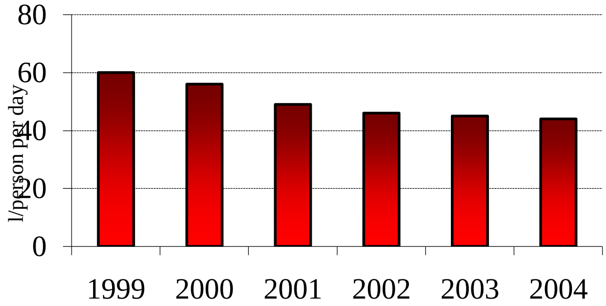

Fig. 4 Dynamics of the average hot water consumption in the buildings analyzed

The changes in DHW consumption (l/(person·d)) during 40 years are presented in Fig.5.

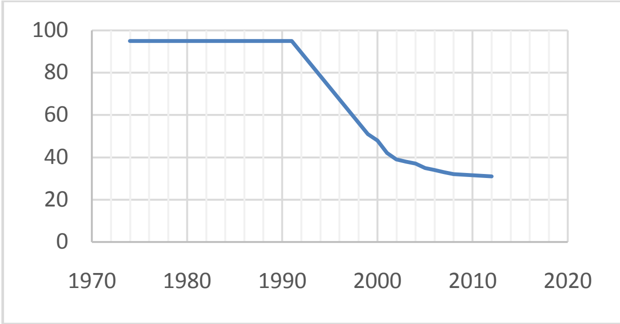

Fig.5. Changes in DHW consumption (l/(person·d)) during 40 years

This considerable reduction in DHW consumption is due to:
- the rapid rise in the price of heat
- the rapid rise in the price of water
- installation of water meters for apartments and the transition to the payment by actual consumption;

but also due to:
- the renovation of the DHW circulation system and its implementation
- the use of lever mixers, modern shower screens and the use of showers instead of the bath
- many people's moderate income.

Comparing the average DHW consumption today with that of the 1970s and 80s, we can see that it has decreased significantly. The change in thermal energy consumption for DHW heating per 1m² of the heated area during 40 years is presented in Fig.6. We see the 2.9 times reduction in energy consumption.

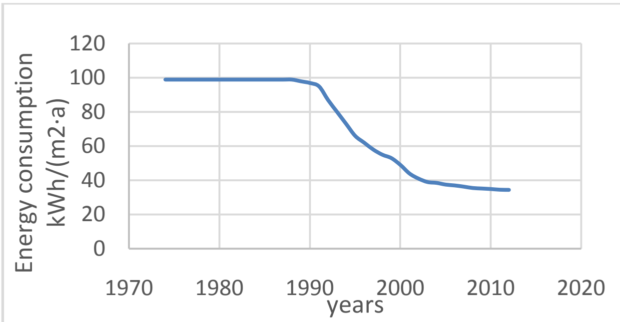

Fig.6. Change in thermal energy consumption for DHW heating during 40 years.

DHW consumption in the 1970s and '80s was characterized by the Soviet Union at that time. 1991 saw a change in the economic formation, the transition from the so-called socialism to capitalism in Estonia. This was accompanied by an increase in fuel prices to the world level. Hot water usage dropped sharply and continued to decrease in the subsequent years.

For reality and requirements to meet, a new method has been proposed for calculating the heating load of DHW instantaneous heat exchangers in residential buildings. The capacity of instantaneous water heaters for heating DHW can be defined by formula (1).

Proceeding from the flow rates obtained by recording DHW consumption in characteristic apartment buildings and their analysis, a new formula (1) for determining the heating load has been worked out. The latter is presented graphically in Fig. 7 (dependence of the heating load on the number of apartments).

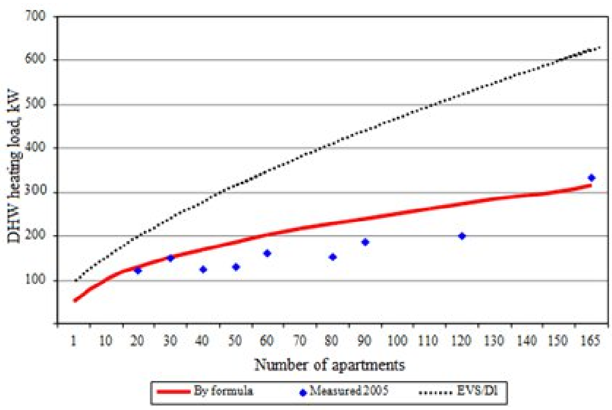

Fig. 7. Dependence of the DHW heating load on the number of apartments in a residential building (by formula (1) and by EVS) together with the points calculated on the basis of the measurement results

The recommended DHW flow rates for residential and public buildings determined by empirical formulas are about two times lower than the values calculated by standard EVS.

The measured points correspond to the loads determined by the maximum DHW consumption in apartment buildings with the given number of apartments in them.

Below we present a formula for determining the heating load of DHW instantaneous heat exchangers if the temperature difference of hot and cold water is 50°C

$$\Phi_{sv} = 30 + 15 \cdot \sqrt{2 \cdot n} + 0.2 \cdot n \qquad (1)$$

where n is the number of apartments.

In every apartment there is a mixer in the kitchen and another one in the bathroom. If the DHW temperature is other than 55°C, a correction factor should be used in determining the load, e.g. at the temperature

60°C – correction factor 1.1 and

65°C – correction factor 1.2.

Figure 7 presents the loads of DHW instantaneous heat exchangers determined for apartment buildings by the proposed formula (1) and by the EVS [17] against the background of the maximum values of the measurement results. Fig. 7 shows that in larger apartment buildings the heating loads of the heat exchangers differ by up to two times.

In Figure 8, added capacity calculated by EN 806-3 is determined on the basis of design flow rates.

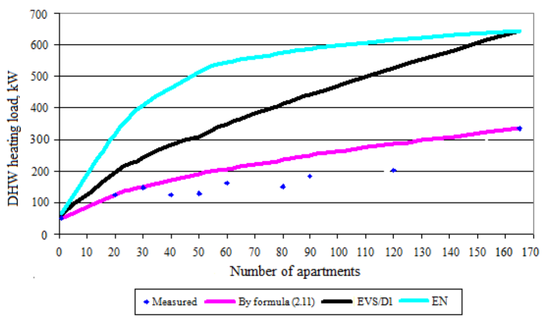

Fig. 8 DHW design heating load depending on the number of apartments by the EVS method, the EN method and the proposed formula together with the points calculated on the basis of the measurement results

Fig.8 shows that standard EN 806-3 is not suitable for determining the design flow rates.

4 DHW consumption in educational and office buildings

It must be pointed out, however, that in a number of types of buildings (e.g. schools, educational institutions, office buildings) the use of a large number of DHW devices (primarily mixers) is very rare, and practically nonexistent. Such a situation leads to a considerable overdimensioning of DHW heating devices as well as the flow rates of the district heating network water necessary for heating DHW.

In recent years, a study of DHW consumption has been carried out in 25 schools and the study buildings of TUT, where hot water is produced in instantaneous water heaters.

The study shows that the design flow rates calculated by EVS 835 for ordinary schools are considerably bigger than the actually measured ones, which in fact results in overdimensioning both DHW instantaneous heat exchangers and control devices.

A new empirical formula is recommended for determining the design flow rates (2) on the basis of which water heating devices are selected for schools and higher educational institutions without swimming pools:

$$q = 0.00352 \cdot N_1 + 0.00075 \cdot N_2 + 0.0009 \cdot N_3 \quad (2)$$

where q is the design flow rate l/s; N_1 is the number of showers, N_2 is the number of students and N_3 is the number of water outlet devices.

By investigation it can be seen that the design flow rates determined by calculation formula (2) are approximately up to two times smaller than those calculated by the EVS standard and about five times smaller than those determined by the EN standard.

The big difference in the actual DHW consumption and the same by standards is caused by the fact that standards are based on decades old situation. Thus, according to the standards the probability consumption does not meet the current situation.

Fig.9 shows the recorded values. It can be seen that in about 50% of the schools with the design flow rates determined by empirical formula (2) the flow rates are considerably smaller, in about 30% of the schools they are somewhat smaller and in 20% of the schools they are equal or somewhat bigger in comparison with standard EVS 835.

At the same time the design flow rates were closer to the actual flow rates as the calculation only slightly depended on the number of water outlet devices, the majority of which are used marginally.

The comparison of the design flow rates determined for schools by the empirical formula, standard EVS 835 and the recorded values is presented in Fig.9.

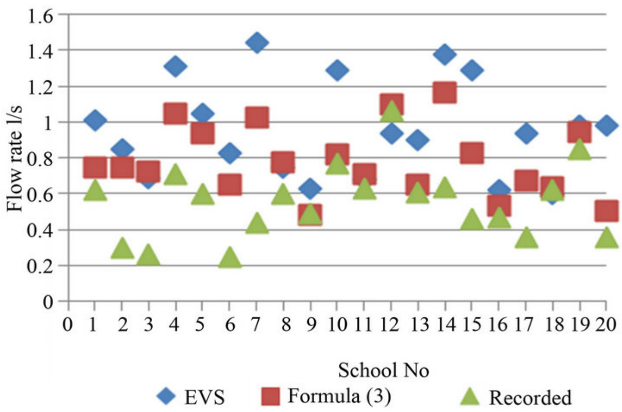

Fig.9. The comparison of the design flow rates determined for schools without a swimming pool by empirical formula (2), standard EVS 835 and the recorded values

As the design flow rates determined by the EVS standard are up to 1.8 times bigger than those measured in kindergartens, a new empirical formula is presented to determine them when selecting water heating devices (3):

$$q = 0.00092 \cdot N_1 + 0.0035 \cdot N_2 + 0.0025 \cdot N_3 \quad (3)$$

where q is the design flow rate l/s; N_1 is the number of showers, N_2 is the number of children, N_3 is the number of water outlet devices.

The design flow rates determined by formula (3) are up to 1.7 times smaller than the ones determined by the EVS standard.

DHW consumption and its variability were studied in 18 office and similar buildings. The actual maximum DHW consumption was compared with the design flow rates determined by standards EVS 835 and EN 806-3.

To determine the design flow rates by standard EN 806-3, the graph of the design flow rate and the sum of normative flow rates was used.

Studies show that the calculated flow rates in office buildings determined by standard EVS are about three times higher than the maximum measured flow rates.

The new empirical formula (4) is recommended for determining the design flow rates in dimensioning the water heating devices for office and public buildings

$$q=0.0082 \cdot N_1+0.0019 \cdot N_2+0.0032 \cdot N_3 \quad (4)$$

where q—design flow rate l/s; N_1—number of showers; N_2—number of people; N_3—number of water outlet devices.

Investigations show that the use of EVS 835: 2003 leads to a most considerable overdimensioning of DHW instantaneous heat exchangers and control devices. The design flow rates of office buildings determined by the Euro standard are not suitable for Estonia, because the results obtained are up to 10 times greater than the measured consumption in office buildings. The reason is that the probability consumption does not meet the current situation.
Studies show that the design flow rates determined by formula (4) are up to two times smaller than those determined by standard EVS and up to eight times smaller than the design flow rates determined by the Euro standard.
Fig. 10 presents a comparison of the design flow rates determined for office buildings by empirical formula (4), standard EVS 835 and the recorded values.
The comparison of the design flow rates determined for office buildings by empirical formula (4), standard EVS 835 and the recorded values (Fig. 10) shows that the flow rates by formula (4) are closer to the actual situation.

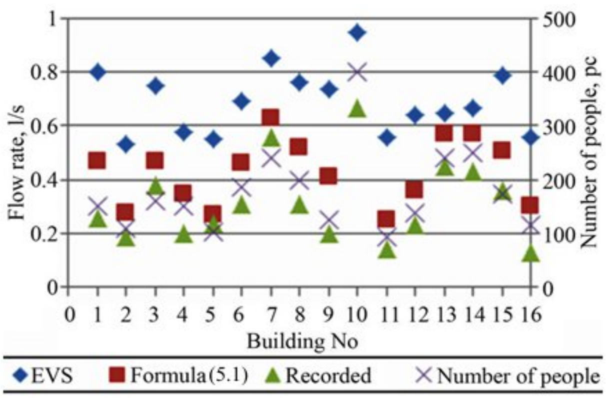

Fig. 10. Comparison of the design flow rates determined for office buildings by empirical formula (3), standard EVS 835 and the recorded values

In a situation in which DHW consumption has drastically reduced, there is an urgent need to develop a new methodology for determining DHW design flow rates.
To reduce energy losses in DHW production:

- the old DHW system should be renovated on the principle of sustainable use of energy
- energy losses into the environment should be reduced by insulating the piping
- piping should be dimensioned with minimum diameters
- the circulation system should be balanced in order to reduce the energy consumption of the circulation pump
- the circulation pump should be switched off while DHW is not being used, e.g. at night (if this is acceptable for consumers)
- DHW temperature should be kept at the minimum level
- advanced temperature controllers should be used
- a suitable DHW production system should be selected for the building, considering the specific characteristics of the building.

5 Results

The optimal calculation methodology of dimensioning the DH network requires the use of the probability of domestic hot water consumption that is close to reality. Long-term studies conducted in Estonian conditions have shown that the probabilistic hot water consumption of apartment buildings can be determined depending on the number of apartments or bathrooms by equation (5)

$$G_{DHW} = 0.2 \cdot n^{0.36} + 0.002 \cdot n \qquad (5)$$

where n is the number of apartments or bathrooms.

The required capacity of hot water heating is determined by (6)

$$\Phi_{SV} = G_{DHW} \cdot c \cdot \rho \cdot \Delta t_{DHW} / 1000 \qquad (6)$$

where Δt_{DHW} – temperature difference between hot and cold water, K.
The cost and maintenance costs of the DH network were compared for the network with 10 consumers (Fig. 11), in two ways:
– using the so-called old method (aggregation of individual consumer loads)
– using the new method of calculation considering the probability of hot water consumption.

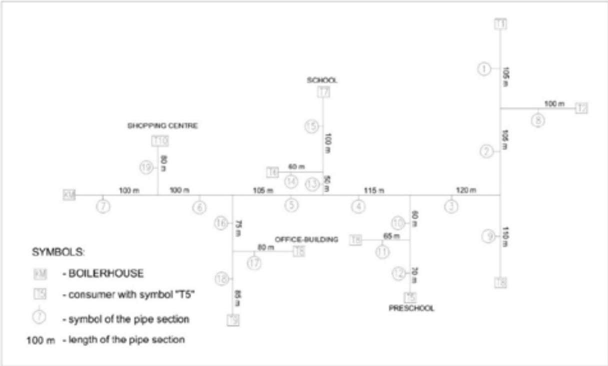

Fig. 11 The calculation diagram of the DH network

Among the hot water consumers in residential buildings there are schools, offices, kindergartens, and shopping centres. For easier design of the DH network and to calculate the probability of hot water consumption, different types of buildings have been converted into residential buildings with an equivalent number of apartments (Table 2).

Table 2 The equivalent number of apartments for schools, kindergartens, office buildings, and trade centres for DHW calculation

Consumer	Design flow rate l/s	Equivalent thermal power kW	Equivalent number of apartments
Office	0.26	52.7	1.1
Kindergarten	0.39	80.8	5.5
School	0.26	53.7	1.2
Trade centre	0.31	64.8	2.6

However, the hot water flow rates of the buildings are determined by the empirical formulas, which have been developed in TUT.
The cost of the DH network is dependent on the diameters of the used pipelines. According to the new calculation methodology, the flow rates are lower and thus it is possible to choose pipes with smaller diameters compared to the old calculation methodology.
The study shows that the thermal network cost is reduced by approximately 12% using the new calculation method. The reduced cost of a new boiler plant with the new calculation method is about 45% lower.
By the new calculation method, the reduction of the heat energy losses of the DH network is nearly 2%.

The pumping costs are determined separately for the heating season and the summer period, when there is only DHW consumption.
The pumping costs are determined on the basis of the pumping power during the period and the duration of the period. The comparison of the new and old dimensioning methods shows that the new method reduces the pumping cost by about 43%.

5 Conclusion

In a situation in which DHW consumption has drastically reduced, there is an urgent need to develop a new methodology for determining DHW design flow rates.
The recommended DHW flow rates for residential and office buildings determined by empirical formulas are about two times lower than the values calculated by standard EVS. As the official methodology for determining the DHW flow rate is not suitable, empirical formulas can be used to determine the design flow rates for the above-mentioned building groups and schools, especially with the modern (read: anti-corrosive) tubing materials.

Instantaneous heat exchangers for DHW systems are of particular importance. Several studies have also pointed out that to heat DHW it would be suitable to use instantaneous heat exchangers [14] instead of tank-type water heaters that would at the same time decrease the risk of Legionella disease.

The new calculation methodology of DHW heaters can significantly reduce duct size in tree-shaped DH networks (approximately 12%), the station power (up to 45%) and maintenance costs.

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