Measurement study on demand of domestic hot water in residential buildings

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Abstract: - The currently running huge substation refurbishing program in Budapest required the surveying of domestic hot water consumption habits that changed greatly in the past 15 years. Using the results of the measurements we worked out a relationship based on probability consideration with a confidence level determined in advance. At a consumer group, characterised with given flat number, the average daily hot water consumption and the duration diagram of the consumption can be determined on at least a confidence level of 99% with the help of the relationship. The domestic hot water production of the heat exchanger and the tank connected in parallel can be simply rated from the duration diagram.

Key-Words: - residential buildings, domestic hot water, measurement of consumption, statistical analysis, probability based rating

1 Introduction

The domestic consumers of district heating in Hungary were subsidized by the state, they paid for the consumed heat a small fragment of the actual cost. The individual meter-accounting of the domestic hot water (DHW) was unknown, consumers paid by lump tariff. Because of the low price and the lack of individual accounting the consumers were not interested in saving of DHW.

For the determination of DHW consumption's design demand an extensive set of measurements were carried out by an expert group leaded by Dr. László Garbai [1]. Being founded on the results of it the standard MSZ-09-85.0004-87 concerning the DHW systems supply more then 25 flats was elaborated [2]. This recommendation gave the peak heat demand and duration diagram of daily consumption at a confidence level of 95% for workdays and of 99% for rest-days. The formulas are suitable for rating of DHW producing systems with heat exchanger and tank connected in parallel (Fig.1). From the 1990s the DHW consumption greatly decreased due to ceasing of the state subsidy for district heating and spreading of individual measuring of the consumption. The rating forms elaborated a few years earlier using outdated principles became unsuitable for rating the DHW producing systems. Using them would have made the heat exchangers and tanks greatly oversized for the decreased consumption. The oversized equipments would result not only in unnecessarily big investment costs: the paradoxical consequence of oversizing, not detailed here, can be energy consuming, exceeding the actual need. The proper method of specification of the DHW demand and sizing of the DHW preparation equipment is a relevant research topic in the field of the district heating [3], [4].

The Budapest District Heating Works Co. Ltd. (Főtáv) has been running a continuous substation reconstruction program from the middle of the 90s. In the process of it the old-fashioned substations with great space demand are changed to compact ones with up-to-date regulation. One of the aims is the minimization of the huge investment costs as far as it is possible, while maintaining satisfactory supply safety. Because of the lack of appropriate design formulas the sizing of the DHW equipment was a problem during the reconstruction. This made necessary the resurveying of DHW consumption habits and the redefinition of the relationships describing them.

2 Preparation of the measurements, basic assumptions

Due to the character of the buildings, the substations planned to be installed contain one or two separately regulated space heating heat exchanger and a DHW heat exchanger connected in parallel with them. On the secondary side of the DHW equipment a tank connected in parallel with the heat exchanger was installed (Fig.1). The heat exchangers are regulated by varying the mass flow of the primary hot water, whose temperature is pre-adjusted as a function of the outside temperature. The substations have DDC (Direct Digital Control) regulators. The reduction of the space demand of the equipments was an important aspect of the reconstruction. It can be achieved by using plate heat exchangers instead of the old-fashioned tube heat exchangers and by roughly reducing the DHW tank's volume, which conventionally was several m^3 before. In favour of it Főtáv changed over from using tanks connected in series to parallel.

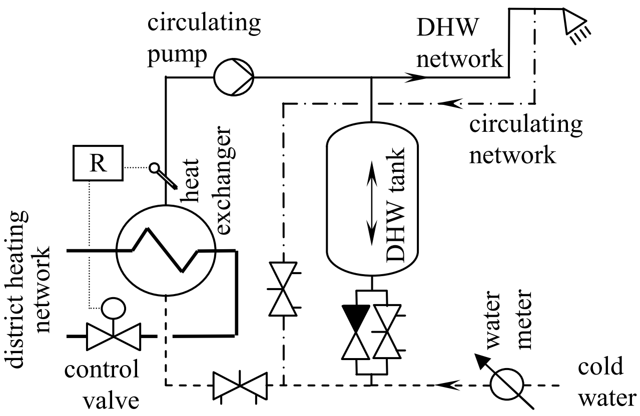

Fig.1 Scheme of DHW producing equipment with parallel tank

2.1 Aims

At the start of the measurements our goal was to work out a set of relationships, which provides results for the rating of DHW producing equipment with a reliability of at least 99%. Even though the form of the DHW consumption change during a measurement in a given building can be very different in different days, the duration diagrams (ordered consumption diagram) taken in the different days are remarkably similar. Therefore we sought a method and relationships to describe the duration diagram accurately for a group of consumers. During the elaboration of the rating formulas our goal was also that those fitting to the present practice should be valid from as low flat number as possible unlike the former low limit value of 25 in [2].

2.2 The method and facility of the measurements

The data received from the measurements must be subjected to statistical analysis due to the random nature of the DHW consumption. The exact expected value and standard deviation of a quantity, which has a known distribution and is proper to a stochastic process, could be calculated from infinite number of measured value. Although a high element number would have been needed to let the confidence range of the statistics' estimation to be narrow enough, made for the sample resulting from the measurements, the number of measurements we could execute were limited by economic rationality.

Based on our prior experiences we could adopt some assumptions on the character of the process that we wanted to measure. We could anticipate that quick and proportionally great changes can take place in the hot water consumption. Theoretically, the continuous registration of the DHW's flow rate would have been needed. The continuous record would have been solely available by an analogue registering, for rational reasons we have chosen digital technique for the data-logging. During the research we were able to apply the former experiences of our occasional flow rate measuring tasks.

Based on our former advantageous experiences we logged the pulses generated by water meters with electric output (read switch). We calculated the average of flow rate of a given period from the number of pulses gathered through that period. The precision of this solution naturally depends on the fineness of the time and flow rate units. We have tried to apply water meters for the data-logging with one pulse by one litre of water flowing through. If the required meter size did not allow using such a meter, then every 10 litres gave a pulse.

We had to find such a technology for carrying out the data-logging, which does not require excessive equipment acquisition and live labour during the measurement program. Under this dual requirement we found that the data-logging capability of the DDC device in the substation and the transmitting of the recorded data to the data centre via mobile telecommunication (GSM) system are very useful. The transmitting of measurement data via GSM system is a relatively recent technology. This self-acting data acquisition system connected with the DDC device was an unprecedented solution in Hungary. We started to apply that with no previous experiences.

The number of free inputs of the substation's DDC device is typically two. We had to determine which parameter has to be logged besides the pulses of the water meter. The flow rate of the consumed DHW, which can be measured in the substation, essentially depends on its temperature, so it is necessary to record it. Nevertheless there is no need to reserve a free input for it, since it is ab ovo an input for the fixed value control of the DHW. The DHW consumption is determined by the DHW temperature which can be measured at the mixing valve. The measurement of this value can not be achieved reasonably. Accepting a certain rate of imperfection in the data processing, the cooling taking place between the substation and the taps can be discarded. For occasional subsequent analyses the return temperature of the circulation network was received and recorded on the remaining input. In the end we took three parameters into the data-logging: the DHW flow rate, the temperature of the DHW produced in the substation, the return temperature of the circulation. Based on the results of previous investigations we assumed that the temperature of the cold water available for the DHW production is nearly constant, 15°C.

Instead of cumulating the pulses of the water meter we have recorded the volume flowing through at intervals of one minute, so in fact we have accomplished the forming of the difference quotient at the level of the data-logging device.

We had to make a decision on the fineness of registration in advance. Based on our previous experiences we have applied a registration cycle of 1 minute [5]. We have done so considering that the shorter the cycle the better for surveying the rapid changes, on the other hand the too frequent registration enlarges the amount of the data and makes the process of it harder.

2.3 Sites for the measurements

The goal of the research was surveying domestic hot water consumption of residential buildings, thus for the investigation we have chosen substations supplying solely flats. The consumption measured in the substation strongly depends on the number of flats. A basic task of our investigation was just the studying of this relationship. That is why we paid particular attention to that the chosen substation properly represents the stock of buildings supplied with DHW, based on the district heating in Budapest. The distribution of the buildings supplied with DHW in Budapest by number of flats is shown on the figure 2. The columns illustrate how many buildings fall into a given range of number of flats. For instance there are 214 pieces of buildings in our registry which has a flat number between 51 and 60. The continuous line represents the cumulated percentage value of the columns.

Flat number range	Number of buildings selected
9-23	10
24-39	10
40-59	10
60-80	10
81-126	10
127-200	10
200-	5

Table 1.
Distribution of selected buildings by flat number

To determine the number of the buildings to be selected, we chose the limits of the ranges of the flat numbers. This way the number of the buildings belonging to those are nearly equal. Cutting the curve of the cumulated building number by 15% we focused on those flat numbers which meant the limits of the ranges. Thus seven ranges have arisen. We decided to select 10 pieces from each of the first six and 5 pieces from the last one (Table 1.).

2.4 Execution of the measurements

During the measurement program, planned as described above for different reasons (not detailed here), data-logging generated valuable results in 55 building for a period between 20 and 35 days. The data-logging at the 55 sites was not carried out at the same time but through a period of more than one and a half year [5], [6].

4 Results and processing

In the 55 sites the registration of the three measured values, sampled minutely, provided more than 5 million pieces of data even after the unavoidable data losses. The raw data were converted to a form which is suitable for a spreadsheet program.

The next task was the filtering of the data. The data collected on weekdays and rest-days were separated, since our initial guess was that there would be a great difference between the consumption habits on weekdays and rest-days. Only the days with complete data series were passed for further process.

The second step of the content filtering was executed on the ordered sets of data. Scrollable diagrams were made form the series. The diagram representation gave a chance for further filtering to enhance the reliability of the statistical analysis. In this process those days were withdrawn from the treatment when outstanding values occurred which were incongruous with the nature of the DHW consumption. These mainly originated from some operating intervention in the substation. Those days were also discarded when some external effect evidently roughly disturbed the normal DHW consumption.
Following the diagram view we could draw some important conclusions. Our initial assumption that the form of the consumption during the weekdays and on the rest-days shows characteristic difference could not been verified. So the distinction of these days in describing a relationship is not reasonable. The next serious lesson was that on the contrary to the [2] standard, as considered earlier, the whole day duration diagram should be investigated. Based on the measurement

results no reliable method could be given to find a shorter continuous designing period. The preliminary analyses confirmed also the aim that the use of the ordered consumption diagram is the best way to describe the intensity of the consumption.

The processing of the data, considered now to be reliable, proceeded with normalizing the flow rates. Applying the measured temperature of the DHW t_m the values of flow rate from the measurement $\dot{V}_m$ were converted to the flow rate $\dot{V}_{norm}$ expected at the uniform designing temperature t_{norm}.

$$\dot{V}_{norm} = \dot{V}_m \frac{t_m - t_{cw}}{t_{norm} - t_{cw}} \qquad (1)$$

where the value of t_{norm} was taken as 50°C,
the value of t_{cw} was taken as 15°C.

Then the duration diagram was made by decreasing order of the time series of the flow rate. At this step we lost an important property of the consumption intensity's form. The peaks of consumption intensity scattered during the day. The consumption calculated from the duration diagram at a τ peak period does not occur in one continuous consumption period. Based on our additional investigations, not detailed here, the sizing took place considering that it makes the application of smaller tanks possible. The rating method we elaborated and show hereafter does not support it; nevertheless with this the rating is shifted toward the greater safety in a degree precisely not known.

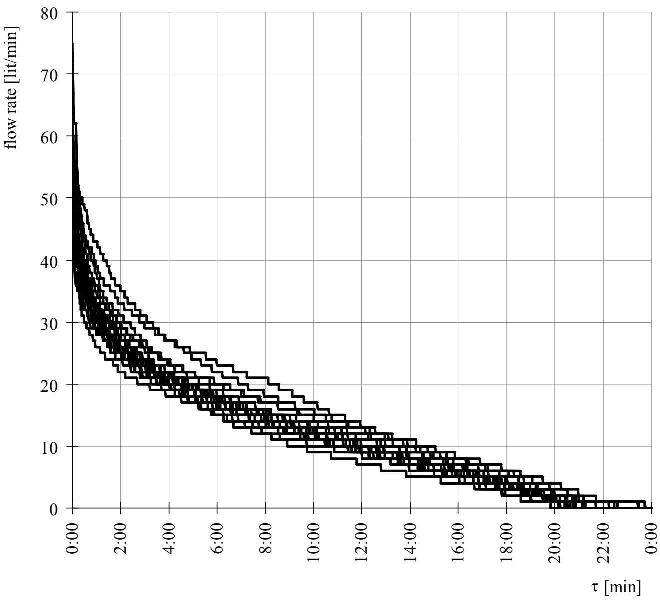

Fig.2 Duration curves of a 79 flat building recorded in 26 different days

In case of each site we gained as many different duration diagrams given by its points as the length of the measuring period. These curves are quite similar to each other (Fig.2). Fixing a peak period in the duration diagrams of a consumer group the related flow rate values can be treated as a statistic sample. During the analyses of the samples based on the central limit theorem the samples were assumed to have a normal distribution [7]. We could have made certain of the adequacy of our assumption with a goodness-of-fit test, but for the proper tests (e.g. χ^2 test) there was not enough data available after filtering the faulty series out. However, we accepted the assumption of the normal distribution, because preliminary investigations carried out with enough data had confirmed it besides the mathematical statistic considerations.

To calculate the value determined by the sample belonging to a given τ peak period the following relationship was applied:

$$\dot{V}(\tau)\Big|_{99\%} = m(\tau) + \xi\sigma(\tau)\,, \qquad (2)$$

where $m(\tau)$ is the expected value of flow rate estimated by the mean value of the sample derived from the measurement; σ is the standard deviation estimated from the sample, ξ is the argument of the standard normal distribution function. The value of ξ belongs to the confidence of 99% is 2.3263.

Determining $\dot{V}(\tau)\Big|_{99\%}$ for every t period a series of points has been obtained. Due to the effort of getting small tank size the first segment was used at the rating of tasks for the actual practice, thus the approximate relationship was sought for the period from 1 to 180 minutes. Based on [2] we expected a relationship in the form below.

$$\dot{V}(\tau) = \frac{a}{\tau} + \frac{b}{\sqrt{\tau}} \qquad (3)$$

In this form it was not possible to find a proper description for the whole required range of 1 to 180 minutes. The relationships in the form of

$$\dot{V}(\tau) = a \cdot \tau^b + c \cdot \tau \qquad (4)$$

gave a quite good approximation for every building in the whole required range. The value of a, b and c were necessarily different at the different buildings. The method of the constant values' determination in the function of the duration diagram of each building in the form of (4) was as follows: The aim was to minimize the sum of the differences between the points of the approximate curve by (4) and the curve derived from the measurements by (2) at a confidence level of 99%, while none of the values of (4) could be smaller than the values of (2) (Fig.3).

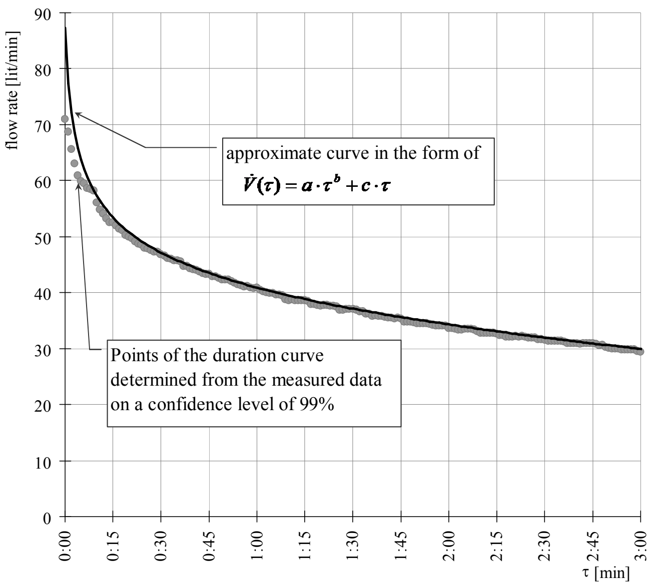

Fig.3 The method of seeking the approximate curve

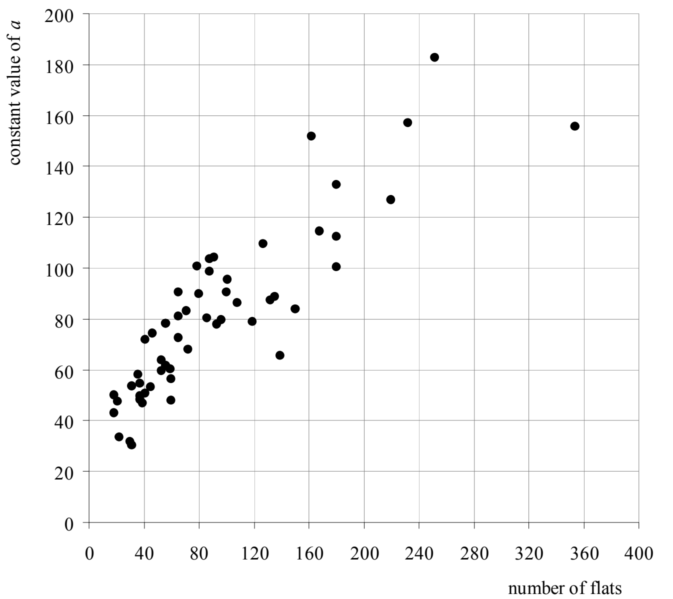

Fig.4 The *a* constant of the approximate duration curve as a function of the flat number

The next task was to describe the relationship of the constants and the buildings. Based on [2] we assumed that the constants are functions of the number of flats, the number of the occupants and the number and types of the consuming places. First, the flat number featuring the building was taken as a base. Though the constants showed a distinctly visible trend when it was represented in a diagram as a function of it, establishing a useful functional relationship was not possible (Fig.4). We obtained similar experiences when we tried to connect the constants of approximation of the duration diagram with the number of occupants which latter data was not too confidential. The type and number of the taps in the district heated flats in Budapest is intensely uniform, its role in the relationship was neglectable.

Nevertheless, the constants of the approximate functions, given for the 99% reliable duration curves of the buildings by (4) (mainly *a* and *b),* showed very strong functional relationship with the daily average consumption that could be calculated from the measured values (Fig.5). This value actually is the quotient of the amount of the DHW consumed under a certain period and the length of that period. Applying this recognition we established the relationships for the constants hereunder:

$$a = 28.623 \cdot \dot{V}_{avg.}^{\;0.4893} \tag{5}$$

$$b = -0.27 \cdot \dot{V}_{avg.}^{\;-0.224} + 0.000813 \cdot \dot{V}_{avg.} \tag{6}$$

$$c = -0.00165 \cdot \dot{V}_{avg.} - 0.0135 \tag{7}$$

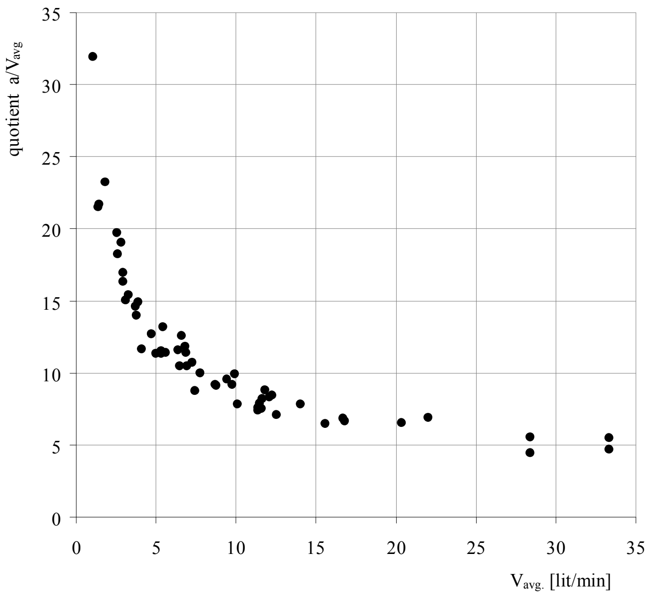

Fig.5 The quotient of *a* constant and $\dot{V}_{avg.}$ as a function of $\dot{V}_{avg.}$

This achievement is a mathematical interpretation of the particular feature that in the initial segment the form of the duration diagram depends on the extent of the area below the curve. That is to say the run of the consumption by the time can be concluded pretty well from the amount of consumed hot water on average. Beyond the sizing of the equipment this feature can be utilized at the enhancing of operating efficiency.

From these consideration, if the daily average consumption of the building was available form former – for instance accounting – measurements, then applying this and relationships (4), (5), (6) and (7) the duration diagram of the building can be produced. This method is not necessarily suitable in every case, and when establishing a rating method all the relationships required to the design of the equipment must be created. Thus, the final task was to find the relationship describing the daily average consumption related to the building.

For this analysis we took the data of the tap water measurement for energetic and cost allocation purposes as a base. These measuring results gave the amount of tap water consumed for the DHW production in an accounting period (typically in a month). As a part of the investigation some filtering was applied to the database. Only the data of those substations remained which solely supply DHW for flats. Beyond that the extremely high or low values, likely to originate from measuring or registration failure, were discarded too. The obtained average flow rate values were represented in a diagram as a function of the number of flats supplied by the substations. To this set of points the

$$\dot{V}_{avg.} = 0.135 \cdot N + 0.3 \cdot \sqrt{N} - 0{,}6 \quad (8)$$

curve have been fitted, which assigns the design value of the average consumption to the number of flats (N) during the design. This relationship corresponded to the form

$$\dot{V}_{avg.} = A \cdot N + B \cdot \sqrt{N} \quad (9)$$

that can be expected on the bases of probability considerations. The importance of the correction value of -0.6 in (8) is significant in case of small flat numbers and means a limitation for the applicability of the formula. The calculation of the average flow rate by (8) is applicable for buildings containing more than 10 flats.
The relationship gives the value of $\dot{V}_{avg.}$ in unit of lit/min. $\dot{V}_{avg.}$ has to be substituted into the equations (5)-(7) in the same unit of lit/min, and applying the constants obtained this way, equation (4) provides the value of the points of the duration curve also in unit of lit/min.

5 Experiences

The description of the duration diagram of a group of DHW consumers is found on the daily average consumption by the relationships elaborated based on measurements. The duration diagram of a newly joining group of consumers can be described based on the relationship elaborated for the daily average consumption, in case of existing consumers the available accounting data can be taken as a base.

The size of the DHW heat exchangers and especially of the tanks could have been reduced by the rating method based on the relationships shown above. At the same time no supply complaint have occurred at any of the substations that hade been refurbished so far.

References:

[1] Lakatos, T., Lipták, A., Garbai, L., Ignácz Cs., Használati melegvíz-csúcsigények meghatározása (Specification of peak demand of DHW), *Épületgépészet*, No.4, 1987, pp. 155-160.

[2] MSZ-09-85.0004-87 A használati melegvíz csúcs-hőteljesítmény-igény meghatározása (Specification of the thermal peak load of the domestic hot water), Hungarian state standard (bill) 1987

[3] Róžalski, J., European guidelines for the preparation of domestic hot water, *Euroheat & Power XXXII. Congress*, Berlin 2005

[4] Tiitinen, M., Dimensioning standard for domestic hot water, *2nd Euroheat&Power RTD Workshop*, Busseles 2006

[5] Lakóépületek mértékadó használatimelegvíz-fogyasztásának meghatározása (Specification of domestic hot water demand of residential buildings); *study*, FŐTÁV Rt. 2005

[6] Dr. Szánthó Zoltán, Némethi Balázs: Használati melegvíz igények meghatározása (Specification of domestic hot water demand); *Vízellátás, csatornázás 2005.*, Vol. 135. 41-44. p

[7] Dougherty, Edward R., *Probability and statistics for the engineering, computing and physical sciences*, Prentice-Hall International, 1990