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Probability theory description of domestic hot water and heating demands

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ABSTRACT

The paper presents the methodology for the risk-based dimensioning of domestic hot water (DHW) and heating demands. It is demonstrated that they are stochastic variables. DHW demands are specified on the basis of hot water consumption statistics in Hungary. The standard values of heat demands for heating are based on the duration curve of external air temperatures. This study discusses daily mean temperature distribution in the heating season – between 15 October and 15 April in Hungary – and the description of its duration curve sorted by time. The authors verify the assumption that the duration curve can be described by normal distribution mathematically with high precision. Thereby they somewhat put an end to the process of mathematical experimentation on what function should be used to describe the frequency and duration curve of external daily mean temperatures in the heating season.

1. Introduction

Most building engineering systems satisfy heating and air conditioning as well as cold and hot water demands. Heating demands are meteorological (weather-based) factors, primarily dependent on external temperature. DHW demands depend on the lifestyle and hygiene levels of consumers. They show a time-of-day course and change randomly. The operation of building engineering systems requires the satisfaction of stochastically changing demands (changing randomly in the course of time). And system design is targeted to install system equipment with dimensions and capacities to enable them to satisfy maximum demand levels occurring rarely and at low rates of probability at the safety levels required. Risk-based dimensioning is applied in building engineering system installation design. Chances of both over dimensioning and under dimensioning must be avoided. In the course of risk-based dimensioning, weather factors can be considered as stochastic variables and their frequency of occurrence and probability are explored. The occurrence of weather factors at a very low probability rate is considered as a so-called nominal state of dimensioning, which is a load state of 1% risk for the most part.

The risk-based dimensioning methodology is obviously a well-known discipline; its proposed application in building engineering was presented in an earlier publication [1]. Both operation and installation design are optimization tasks controlled by economic target functions nowadays. Systems must be designed in a way that the aggregate cost of system development and operation should reach a minimum and should enable the satisfaction of demands at a minimum cost consciously and verifiably. In this respect, our study presents a methodology for the risk-based determination of DHW demands and heating demands. It is demonstrated that both hot water demands and heating demands are stochastic variables and their distribution is described by standard distribution.

2. The probability feature of domestic hot water demands

Previously literatures do not investigate the DHW and heating demands based on probability theory [6–12].

DIN 4708 standard describes the calculation method of the DHW demand based on deterministic point of view. In the standard is no risk-based approach. This paper presents the necessity of aspect change and gives solution [5].

In respect of consumer groups of a discretionary number of apartments, the quantity and intensity of consumption at any time of day and for any period present random and unpredictable fluctuations, therefore they can be considered as stochastic variables and can be described by probability function relations. In case of

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Nomenclature

Q_{DHW}	DHW consumption
n	the number of apartments
m_{DHW}	the expected value of DHW consumption
σ_{DHW}	the standard deviation of DHW consumption
ξ	the abscissa value of standard normal distribution at the required reliability level (e.g. 99%)
$\dot{V}_{average}$	the daily average consumption intensity
$\dot{V}_{DHWEC}$	the capacity of the DHW heat exchanger
τ_{disch}	duration of discharge
λ_{St}	Student distribution
s^*	adjusted empirical standard deviation
m	the expected value of daily mean external temperature
σ	the dispersion of daily mean external temperature

consumption for any period of time, consumption is characterized by its density and distribution functions. The distribution function is generally normal, determined by two of its parameters, namely the expected value and standard deviation, which are to be specified by measurements. In case of domestic hot water consumption and intensity for any period of time, we are interested in the so-called standard values. Standard values are characterized by the fact that by definition, it can be expected at a 95 or 99% reliability rate that no higher values occur in the consumption period examined. The standard value of consumption for a certain period of time at a time of day:

$$Q_{DHW} = m_{DHW} + \xi\sigma_{DHW}. \quad (1)$$

Remark. Based on measurements and statistic tests DHW consumption is described by normal distribution of probability variables. We introduced the standardized form of the probability variable as:

$$\xi = \frac{Q - m_{DHW}}{\sigma_{DHW}}.$$

Values of standard normal probability distribution are in the table [13]. ξ value could be calculation from the table [13]. The design DHW value could be calculation in given reliability level.

Standard consumption for a period of time, using the simplifying concept of the so-called apartment unit (average apartment), in function of the number of apartments, at a time of day:

$$Q_{DHW}(n) = n\, m_{DHW} + \xi\sqrt{n}\sigma_{DHW}, \quad (2)$$

where Q is DHW consumption, n is the number of apartments, m_{DHW} is the expected value of DHW consumption, σ_{DHW} is the standard deviation of DHW consumption, ξ is the abscissa value of standard normal distribution at the required reliability level (if e.g. 99%, $\xi = 2.33$).

The expected value and standard deviation of DHW consumption of a required period can be determined by means of mathematical statistics based on measurements. It is expedient to carry out measurements for various types of buildings and a variety of numbers of apartments, and to correlate the figures of expected value and standard deviation to an apartment unit.

Fig. 1 shows the qualitative image of standard consumptions in function of the number of apartments.

The methodology for determining the standard values of domestic hot water consumption on a probability theory basis was developed by Garbai and Lakatos [2].

Intensity curves and calculation formulas of standard domestic hot water consumptions of different durations are summarized in the German (DIN 4708) and the Hungarian standards. The

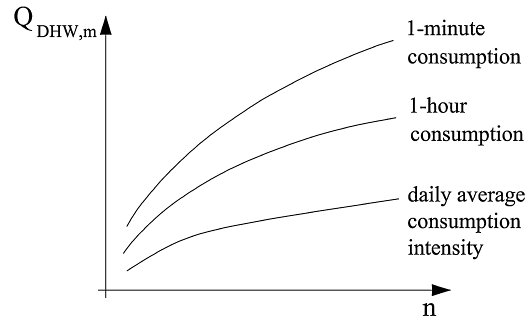

Fig. 1. Qualitative of standard domestic hot water consumption.

Hungarian standard was developed in the 1980s on the basis of unmeasured hot water consumption statistics. It is not recommended any longer to apply the values and formulas published therein as they yield considerably higher consumption figures than actual figures based on currently measured consumption rates.

In 2004 and 2005, the hot water consumption of a number of buildings was measured by Budapest District Heating Company on an on-going basis, the figures yielded were processed and values and calculation formulas of 99% reliability were worked out in order to determine the duration curves of consumptions and consumption intensities of various periods of time (minute-based consumptions) [4].

The following expression can be used to describe the 99% reliability level sorted duration curve function of consumption intensities.

$$\dot{V} = A\,\tau^{B} + c\,G\,\tau \quad [\mathrm{l/\,min}], \quad (3)$$

where

$$A = 28.623\,\dot{V}_{average}^{0.4893}, \quad (4)$$

$$B = -0.27\,\dot{V}_{mean}^{-0.224} + 0.000813\,\dot{V}_{average}, \quad (5)$$

$$C = -0.00265\,\dot{V}_{average} - 0.0135. \quad (6)$$

$\dot{V}_{average}$ is the daily average consumption intensity [l/min].

The formula expresses the duration of a consumption intensity value or a higher value at 99% reliability level.

The daily average consumption intensity of 99% reliability level can be determined by the following formula:

$$\dot{V}_{average} = n \cdot a + 2.33\sigma\sqrt{n}, \quad \dot{V}_{average} = 0.135\,n + 0.3\sqrt{n} \quad [\mathrm{k/min}]. \quad (7)$$

The formula indicates that the probability distribution of daily average consumption intensities follows normal distribution. The expected value for 1 apartment is $a = 0.135$ l/min, and the standard deviation for 1 apartment is $\sigma = 0.128$ l/min.

Based on our investigations, it has been demonstrated that the quantity of hot water consumed in a peak consumption period of discretionary duration also indicates normal distribution. Table 1 shows the expected value and standard deviation of the quantity of hot water consumed in a given period in function of the peak consumption period. Fig. 2. shows consumption.

Units of measure applied in the table:

$$a\left[\frac{1}{\mathrm{apartment}}\right],$$

$$\sigma\left[\frac{1}{\mathrm{apartment}}\right].$$

Quantity of consumption at 99% reliability level in case of an n number of apartments, using the data in Table 1: $V = n \cdot a + 2.33\sigma\sqrt{n}$.