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Risk-based determination of heat demand for central and district heating by a probability theory approach

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ABSTRACT

One of the most important design tasks related to the establishment and operation of heat supply systems involve design heat demand of a required reliability level. Determination of heat demand for central and district heating is set out in standards in the practice of both Hungary and most European countries. Methodologies reflect a deterministic tendency. The uncertainty of heat demand for heating so specified is not analyzed: values are not associated with reliability, probability and confidence interval figures. Our article presents the method of risk-based determination of heat demand for central and district heating by probability theory approach.

1. Introduction

One of the most important design tasks related to the establishment and operation of heat supply systems involve design heat demand of a required reliability level. Heat demand can be for heating and for domestic hot water.

It is a fact in heat supply that both heat demand for central and district heating are random, meaning that they depend on a number of factors, and they cannot be forecasted accurately. They can be specified primarily by a probability approach [1].

In terms of tendency and volume, heat demand for heating are linked to the magnitude and frequency of occurrence of external meteorological factors, especially external temperature and winds. Demand for domestic hot water change absolutely randomly: their size depends, in the stochastic sense, on the number of homes supplied and the number of inhabitant consumers.

Brochus et al. [3] presented the quantification of uncertainty in predicting building energy consumption with stochastic approaches to building energy use. A probabilistic approach for the thermal performance of a building envelope was published by Pietzyk [4]. Wang et al. [6] investigated the uncertainties in energy consumption introduced by building operations and weather for medium-size office building. Nagai and Nagata [7] presented the probabilistic approach to determination of internal heat gains in office buildings for peak load calculation. Pedersen et al. [8] presented the load prediction method for heat and electricity demand in buildings for the purpose of planning for mixed energy distribution systems. Hovgaard et al. [11] investigated model predictive control technologies in refrigeration systems. Rezvan et al. [12] presented the optimization of distributed generation capacities in buildings of uncertainty in load demand for combined heat and power units. A research group in Sweden [13,14] investigated a multi-agent approach to deliver hot water just in time to the district heating system. Simulation models have also been developed [5]. However, specialists have not yet dealt with the risk-based determination of heat demand.

Design heat demand means a maximum of heat demand which occurs at a less than 1% frequency rate (lasting for 24 h) in the coldest appreciable external weather conditions (between −13 and −15 °C).

A maximum design value is also characteristic of demand for domestic hot water. It is required to be determined in order to specify production capacity volumes. This issue was discussed in [2]. This paper analyzes the uncertainties of heat demand for central and district heating by applying a mathematical probability theory. Uncertainty can be examined in terms of the heat demand of an apartment or a building, or the total heat demand of a district heating system. Uncertainty of the total system can be built up from the heat demand uncertainties of apartments and buildings (expected value, standard deviation and confidence interval). This has been termed as the synthetic method. The uncertainty of

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the resultant heat demand of a system can also be determined from measured values by using correlation and regression analysis tools. Both methods are presented in our study.

It can be stated on this basis to what extent it is likely that actual heat demand will not exceed a prescribed value at a certain time of day, a function of the external meteorological condition, and taking a certain number of homes as a basis.

Even in daily operational practice, it is very important to know the rate of heat demand expected to occur, and accordingly, the schedule to be applied as well as the forward water temperature and mass flux to be planned.

The method outlined here is used for finding new ways and means to specify various demands in building engineering design, hoping that oversized building engineering systems – including their investment and operating costs – can be reduced. So far, our investigations suggest that 10–15% capacity reserves can be found by these methods compared to the results of calculations performed according to a deterministic approach.

The following is a presentation of the theory of this analysis.

2. Probability character of heat demand for central and district heating in case of an apartment or a building

First of all, let us examine the determination of apartment and building heat demand and the arising uncertainty in a probability field. As mentioned in the introduction, the uncertainty of the heat demand of apartments or buildings can be used for building up the uncertainty of the heat demand of the entire district heating system synthetically. Heating aims to ensure agreeable comfort parameters for those who are staying within a space of residence, primarily pleasant air temperatures (based on [9], 20–24 °C pertaining to category II) on an on-going basis.

Heat demand for heating for an apartment:

$$\dot{Q} = \sum U \cdot A \cdot \Delta t + \sum \dot{V} \cdot \rho \cdot c \cdot \Delta t + \sum \dot{Q}_b - \sum \dot{Q}_k, \tag{1}$$

where U is the heat transmission coefficient; A is the delimiting surface; $\dot{V}$ is the volumetric flow of filtration; Δt is the difference between internal and external temperatures where the internal temperatures is a prescribed or a given value set by the consumer; $\dot{Q}_b$ means the heat output of internal heat sources, internal heat gain, and the heat output of household machinery and people; $\dot{Q}_k$ means external heat sources (solar radiation); i number of apartments.

For one building, formula (1) is used for summarizing the heat demand determined for each apartment accordingly.

In this context, all factors are probability type: they cannot be specified exactly and they change randomly. As a consequence, heat demand $\dot{Q}$ for heating is a probability type factor, a probability variable in the mathematical sense. Heat gain from solar radiation and from heat produced within the building is also random. Therefore, heat demand for heating involves uncertainties and has a probability nature even in case of given external meteorological conditions.

A probability variable is determined by the type of probability distribution, distribution parameters, the expected value and standard deviation.

In the course of design, it cannot be forecasted accurately the actual values of U, A and V cannot be forecasted accurately as opposed to plans, and it cannot be stated what values are assumed by U and $\dot{V}$ in case of equipment in operation in certain weather conditions. The figures realized are unknown and uncertain compared to design values, meaning that they represent probability variables. It should also be added that the values of heat transfer and heat transmission coefficients affecting heat transmittance – as set out in manuals – similarly involve uncertainties, so they also constitute probability variables. Obviously, internal temperatures are also within a certain range: their values are set by consumers, so they are also of the probability type.

Determination of the so-called standard (nominal) heat demand is set out in the currently effective standard or regulation of heat demand design. The calculations and dimensioning procedures described in the standard are deterministic. Designers are required to analyze and calculate the uncertainty and the probability distribution of figures calculated according to standard specifications.

2.1. Devise of the design (nominal, maximum) heat demand for heating

In the design of a heated object, the design heat demand for heating is specified as follows:

Assignment: to seek for the maximum of expression (1) at a prescribed reliability level:

$$\dot{Q}_n = \max_{\Delta t} \left\{ \dot{Q} = A \cdot U \cdot \Delta t + \dot{V} \cdot \rho \cdot c \cdot \Delta t - \dot{Q}_b - \dot{Q}_k \right\},$$
$$R = P\left(\dot{Q} \geq \dot{Q}_n\right) \leq 0.01, \tag{2}$$

where R is the chance of occurrence of a heat demand exceeding the design heat demand (representing the risk).

Theoretically speaking, all the variables in the equation are known design values, but the states actually realized are of the probability type.

Based on the statistics of local meteorological factors, the external design temperature is usually −10 to −15 °C.

In the expression above, R designates the rate of risk, specified at 1% in general for design in practice.

The equation must be solved for each of the values −10 to −15 °C, and the expected value and standard deviation of the rest of the factors are analyzed for each value assumed. It can be presumed that standardized, the so-called 'required heat' calculations yield the expected value of heat demand. Our task is to analyze the uncertainties of the influencing factors $U, A, \dot{V}, \dot{Q}_b, \dot{Q}_k$.

Distribution of the function $\dot{Q}$ can be determined partly by calculations and partly by measurements on basis of the distribution of variables. The method for this is presented below. Correlation (2) includes multiplications and an addition; accordingly, it should be investigated how to calculate the distribution parameters of the product and sum of probability variables.

2.2. Sum of two probability variables

2.2.1. Density and distribution functions

In order to determine the probability distribution of the sum of two probability variables, let us take probability variables x_1, x_2 of joint density function $h(x_1,x_2)$ and probability variable $y = x_1 + x_2$.

If the joint density function of probability variables x_1, x_2 is $h(x_1,x_2)$, then the density function of their sum $y = x_1 + x_2$ will be

$$g(y) = \int_{-\infty}^{\infty} h(x, y-x)dx = \int_{-\infty}^{\infty} h(y-x, x)dx. \tag{3}$$

In view of the density function of the sum, let us calculate the distribution function of $y = x_1 + x_2$ as well.

$$G(y) = \int_{-\infty}^{y} \int_{-\infty}^{\infty} h(x, z-x)dxdz = \int_{-\infty}^{y} \int_{-\infty}^{\infty} h(z-x, x)dxdz. \tag{4}$$

If x_1 and x_2 are independent probability variables, $h(x_1,x_2) = f_1(x_1)f_2(x_2)$ (where $f_1(x_1)$, and $f_2(x_2)$ are the density