
RELIABILITY ASSESSMENT OF HEAT SUPPLY SYSTEMS IN THEIR OPERATIONAL PROCESS

Bożena Babiarz



Rzeszów University of Technology, Rzeszów, Poland

e-mail: bbabiarz@prz.edu.pl

ABSTRACT

This paper presents an analysis of the operational process of heat supply system, taking into consideration its reliability. The specific character of the operation of heat-supply systems has been considered in this work. In the process of exploitation of heat-supply systems five operational states have been distinguished, using as a criterion the level of indoor temperature decrease in residential rooms. The method of modelling the reliability of heat-supply systems is worked out. The methodology of determining the overall index of heat-supply system reliability has been presented. The measure of heat-supply system reliability has been taken to be as the scale/quantity of inadequate supply of heat power at a given state. Calculations have been carried out regarding the changeability of exterior conditions for one of the groups of customers – residential users. On the basis of the operational data for the heat supply system with two heat sources, shortfalls of heat power and the probability of their occurrence have been calculated as an application of this methodology.

1. INTRODUCTION

Reliability is the primary factor of utility, that is, the ability of a technical system to meet human needs, which directly determines the practical possibilities of realizing the aims of the system (tasks). Even if technical systems are perfect in a functional sense, they become useless if the level of their reliability is not satisfactory - if it is lower than required (Barlow, 1993)]. The reliability of a heat-supply system is closely connected with the reliability of its parts (sub-systems, structures), which determines the quality of the completing tasks by the system after taking into consideration random changes of the functional characteristics of the given system with the existence of computational external conditions (Babiarz, 2002)]. The description of reliability is closely connected with the description of the functioning process of heat-supply systems, considering changeable external conditions. Determining the influence of the conditions on the reliability of heat-supply systems and considering appropriate criteria, is an inseparable part of the analysis of an operational process of the system. Heat-supply systems may be included in the class of relatively complex technical systems. Each of them constitutes a functional whole, divisible into sub-systems, structures and elements connected with the climate, the environment and the demand for heat and are characterized by random changes of their states. The characteristic feature of heat-supply systems is the occurrence of many operational states of the system at various heat loads and efficiencies, determined by a range of random factors affecting the demand for heat. From the standpoint of reliability, the states are described by a combination of damaged and undamaged elements connected with each other by means of appropriate structures. In this work, basic assumptions for modelling and analysis of the reliability of heat-supply system units are presented, considering the diversified operational abilities of heating systems.

2. RELIABILITY STATES OF OPERATIONAL PROCESS IN A HEAT SUPPLY SYSTEM

In the process of the exploitation of heat-supply systems five operational states have been distinguished: (A), (B), (C), (D) i (E) (fig.1), assuming as a criterion the level of indoor temperature decrease in residential rooms T_i [$^{\circ}\text{C}$] and the time of the duration of interference in heat supply for consumers t_n [h], caused by failure (Babiarz, 2002 & 2003).

The state of complete ability (A) – referred to as the state of operational reliability – the state which determines the situation where the indoor temperature is equal to the computational indoor temperature for the majority of residential rooms $T_{iA} = T_{io} = 20$ $^{\circ}\text{C}$ and there is no interference in heat supply: $Q_A = Q_n$, Q_n [MW] – termed ordered heat power.

The state of partial permissible ability (B) – the state of permissible operational reliability, there are certain limitations in heat supply displaying a decrease in heated rooms temperature to $T_i=15^{\circ}\text{C}$, taken as a border, at which the human organism is able to function normally. It corresponds with a decrease in heat power supplied to consumers: $\alpha_B Q_n \leq Q_B < Q_n$.

The state of partial limited ability (C) – the state of limited operational reliability where considerable difficulties connected with the necessity to make use of other heat sources for heating (electric energy, natural gas etc.) are observed. The heating equipment is only protected against freezing by maintaining a minimal temperature $T_{iC} = 8^{\circ}\text{C}$ due to the supply of heat power: $\alpha_C Q_n \leq Q_C < \alpha_B Q_n$.

The state of complete disability (D) – the state of operational unreliability, when border indoor temperature is equal to $T_{iD}=0^{\circ}\text{C}$ and heat power is contained between: $\alpha_D Q_n \leq Q_D < \alpha_C Q_n$.

The state of disaster (E) – the state where the water in the central heating system freezes, resulting in damage to the system. There is also a threat to human life as a consequence of loss of heat power supply: $Q_E \leq \alpha_D Q_n$.

Changes of heat power value in particular states have been calculated according to introduced factors of heat power decrease: α_B , α_C , α_D . The ordered heat power in a given heat supply system Q_n has been taken as its capacity. It has been determined as production capacity Q_p . The scheme of the above operational states of heat supply system described is given in Figure 1.

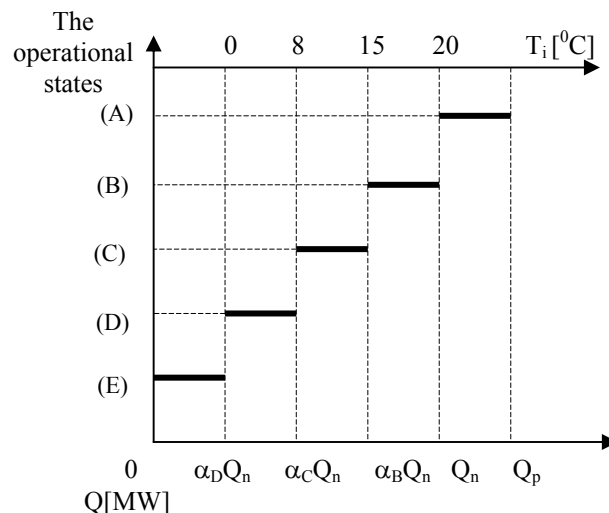


Figure 1. Classification of operational states of heating system depending on heat power Q [MW] and indoor temperature T_i [$^{\circ}\text{C}$]

Factors of heat power decrease: α_B , α_C , α_D have been calculated from the proportion of heat losses Q_{str} in buildings, considering particular states in different exterior conditions which were determined by the level of outdoor temperature T_e .

Reductions of operational parameters in higher than computational temperature conditions do not always mean the disability of the entire heat supply system. Therefore, the following considerations have been carried out in six variants for different external temperatures T_e (-20, -15, -10, -5, 0, +5 °C) and their duration.

$$Q_{strAx} = k_b \cdot A_b \cdot (T_{iA} - T_{ex}) \quad (1)$$

$$Q_{strBx} = k_b \cdot A_b \cdot (T_{iB} - T_{ex}) \quad (2)$$

$$Q_{strCx} = k_b \cdot A_b \cdot (T_{iC} - T_{ex}) \quad (3)$$

$$Q_{strDx} = k_b \cdot A_b \cdot (T_{iD} - T_{ex}) \quad (4)$$

Where: T_{iA} , T_{iB} , T_{iC} , T_{iD} – indoor temperature appropriate to the state (A), (B), (C), (D); T_{ex} – external temperature taken for x - variant; k_b – overall heat-transfer coefficient of the building; A_b – surface of the cooling division wall in the building;

The factor of permissible heat power decrease in heat supply system α_{Bx} in state (B) for variant x has been determined from the proportion of heat losses in the building in state (B) to heat losses in the state of complete ability (A) given by

$$\alpha_{Bx} = \frac{Q_{strBx}}{Q_{strAx}} = \frac{T_{iB} - T_{ex}}{T_{iA} - T_{ex}} \quad (5)$$

Similarly from the proportion of heat losses in the building residual factors: α_{Cx} , α_{Dx} have been determined: α_{Cx} – the factor of limited heat power decrease in state (C) for variant x; α_{Dx} – the factor of border heat power decrease in state (C) for variant x;

$$\alpha_{Cx} = \frac{Q_{strCx}}{Q_{strAx}} = \frac{T_{iC} - T_{ex}}{T_{iA} - T_{ex}} \quad (6)$$

$$\alpha_{Dx} = \frac{Q_{strDx}}{Q_{strAx}} = \frac{T_{iD} - T_{ex}}{T_{iA} - T_{ex}} \quad (7)$$

Information about heat power supply Q_{ix} in the particular states, demonstrating differences between variants, is presented schematically in Figure 2 in the following formulas:

$$Q_{Ax} \geq Q_n \quad (8)$$

$$\alpha_{Bx} Q_n \leq Q_{Bx} < Q_n \quad (9)$$

$$\alpha_{Cx} Q_n \leq Q_{Cx} < \alpha_{Bx} Q_n \quad (10)$$

$$\alpha_{Dx} Q_n \leq Q_{Dx} < \alpha_{Cx} Q_n \quad (11)$$

$$Q_{Ex} < \alpha_{Dx} Q_n \tag{12}$$

Q_n – nominal heat power determined as ordered heat power, resulting from detailed heat losses for individual conditions.

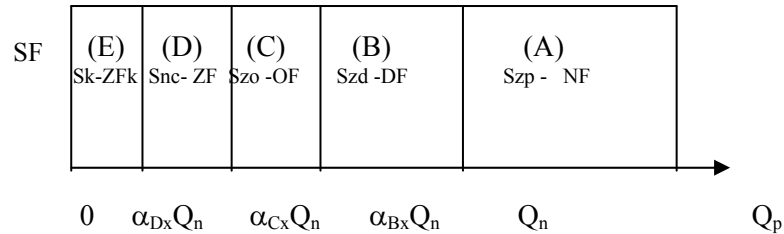


Figure 2. The operational states of heat supply system as a function of heat power

Values of border parameters determining particular states of the system in the considered variants have been calculated according to the formulas (5, 6, 7) and presented graphically in Figure3.

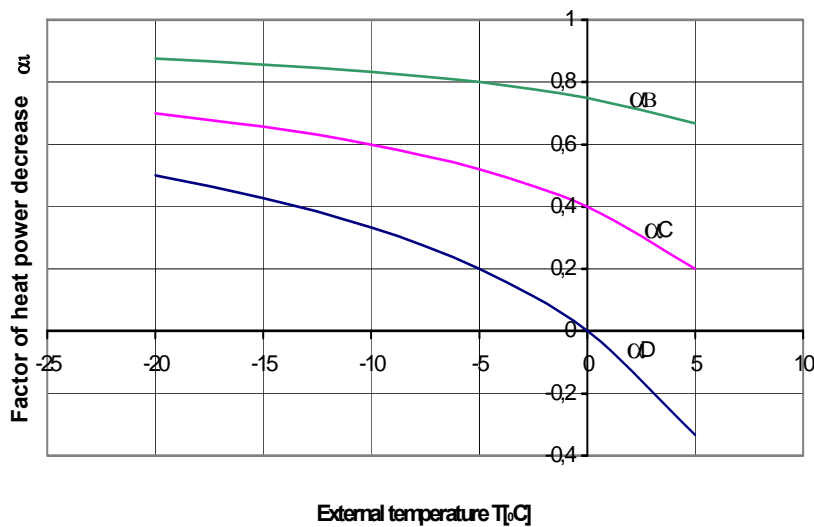


Figure 3. Relationship between factors of heat power decrease and external temperature considering changeable external conditions

Factors of heat power decrease diminish along with an increase in external air temperature.

3. THE METHOD OF RELIABILITY ASSESSMENT

Elements which I have obtained from the division of heat supply system and I can't divide them because they are indivisible in this stage of thinks, I treat as two-state (element operate or completely don't operate) and renewable (we can renew it to work, it can be repaired).

The stationary preparedness index K_{el} determining the probability of finding an element (el) at any time being in the ability state, is taken as a measure of operational reliability of two-state objects.

As a measure of operational reliability of that two-state elements I have taken the stationary preparedness index K_{el} which determine the probability of finding an element (el) in working order at any time, probability that the element will realize its tasks according to its intendment in the way which give to customers possibility of its using without any interruptions, impediment and limits.

$$K_{el} = P(Sz_{el}) = \frac{E(t_z)}{E(t_z) + E(t_n)} \quad (13)$$

Stoppage index for element:

$$U_{el} = 1 - K_{el} \quad (14)$$

Two-state objects can remain in numerous operational states depending on the degree of meeting attributed requirements. Owing to the specific character of heat supply systems, it is permitted to operate this system with decreased parameters in specific operational conditions and time (Babiarz 2006).

The measure of reliability is a shortfall of heat power ΔQ_i in i-state for conditions describing variant x.

$$\Delta Q_i = Q_{nix} - Q_i \quad (15)$$

where:

Q_{nix} – heat power in consider i- state for variant x; Q_i – heat power equivalent to aggregated heat power of heat sources in particular states;

$$Q_{nix} = \varphi_x \cdot Q_n \quad (16)$$

when: φ_x - load factor for variant x;

$$\varphi_x = \frac{T_{io} - T_{ex}}{T_{io} - T_{eo}} \quad (17)$$

The overall index of heat-supply system unreliability U_u has been evaluated. It determines the relation of expected heat power shortage $E(\Delta Q)$ to ordered heat power value Q_n which results from detailed heat loss balances for individual conditions.

$$U_u = \frac{E(\Delta Q)}{Q_n} \quad (18)$$

The overall index of heat-supply system reliability K_u , which is a measure of reliability in a heat supply system operation, can be calculated with the use of the following formula:

$$K_u = 1 - U_u \quad (19)$$

4. AN EXAMPLE OF APPLICATION OF THE DERIVED METHOD

Calculations have been carried out for the heat supply system in the city of Rzeszów, which consists of two interconnected heat sources signed as UZC I and II. Ordered heat power for this system equals $Q_n = 407$ MW. For the two heat sources $y = 5^2 = 25$ reliability states have been considered. On the basis of the operational data (Babiarz, 2002), shortfalls of heat power and the probability of their occurrence have been calculated. Results of the calculation of the overall indexes of heat-supply system reliability for one variant determined by the level of external temperature T_e are presented in Table 1.

Heat power value for this variant evaluated according to the formula (16) equals

$$Q_{nI} = Q_n = 407 \text{ MW},$$

because according to formula (17):

$$\varphi_I = 1$$

Table 1. Calculation of shortfalls of heat power and the probability of their occurrence in particulars operational states in the city of Rzeszow for variant I

SF	UZC		P_i	Q_i [MW]		ΔQ [MW]	$E(\Delta Q)$ [MW]
	I	II		I	II		
1	A	A	0,701053	327,0	80,0	0	0
2	A	B	0,093475	327,0	75,0	5	0,467373
3	A	C	0,049758	327,0	63,0	17	0,845879
4	A	D	0,010851	327,0	52,5	27,5	0,298413
5	A	E	0,000576	327,0	40,0	40	0,023036
6	B	A	0,090406	306,5	80,0	20,5	1,85333
7	B	B	0,012054	306,5	75,0	25,5	0,307385
8	B	C	0,006416	306,5	63,0	37,5	0,240624
9	B	D	0,001399	306,5	52,5	48	0,06717
10	B	E	0,000074	306,5	40,0	60,5	0,004493
11	C	A	0,020378	257,5	80,0	69,5	1,416337
12	C	B	0,002717	257,5	75,0	74,5	0,202433
13	C	C	0,001446	257,5	63,0	86,5	0,125114
14	C	D	0,000315	257,5	52,5	97	0,030598
15	C	E	0,000017	257,5	40,0	109,5	0,001833
16	D	A	0,007182	196,5	80,0	130,5	0,937303
17	D	B	0,000958	196,5	75,0	135,5	0,129763
18	D	C	0,000510	196,5	63,0	147,5	0,075192
19	D	D	0,000111	196,5	52,5	158	0,017566
20	D	E	0,000006	196,5	40,0	170,5	0,001006

21	E	A	0,000233	164,0	40,0	163	0,038058
22	E	B	0,000031	164,0	40,0	168	0,00523
23	E	C	0,000016	164,0	40,0	180	0,002983
24	E	D	0,000003	164,0	40,0	190,5	0,000688
25	E	E	1,91E-07	164,0	40,0	203	3,89E-05
			Σ 1.0				7,091847

Where: A - describes a situation when the heat source (UZC I or II) is in the state of complete ability (NF-Szp), B - describes a situation when the heat source (UZC) is in the state of partial permissible ability (DF-Szd), C - describes a situation when the heat source (UZC) is in the state of partial limited ability (OF-Szo), D - describes a situation when the heat source (UZC) is in the state of complete disability (DF-Snn), E - describes a situation when the heat source (UZC) is in the state of disaster (ZF-Snk).

The overall index of heat-supply system unreliability for the first variant is given as:

$$U_I = \frac{E(\Delta Q)}{Q_n} = \frac{7,0918}{407} = 0,017425$$

The overall index of the heat-supply system reliability for the first variant is given as:

$$K_I = 1 - U_I = 0,982575$$

Calculations of the overall index of the heat-supply system reliability for every variant described by external temperature had been carried out. Results of the calculations of the overall indexes of heat-supply system reliability, accounted for by means of an analysis of states, which can take place in an operation process of heat supply system, are presented graphically in Figure 4.

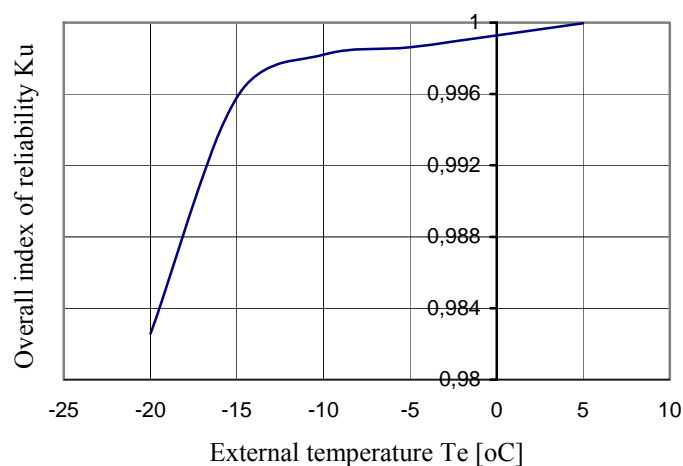


Figure 4. Dependence of overall index of heat-supply system reliability on external temperature

Along with an increase of external air temperature T_e , reliability of the heat supply system increases, whose measure is the overall index of heat-supply system reliability. The index takes a minimal value $K_u = 0,982575$ for variant I of computational conditions, with $T_e = -20$ °C, and a maximal value $K_u = 0,999972$ for variant VI, with external temperature $T_e = +5$ °C.

5. SUMMARY

The specific character of the operation of heat-supply systems has been presented in this work. A model describing the functioning of heat-supply system structures in the aspect of reliability has been developed. In the process of the exploitation of heat-supply systems five operational states have been distinguished, assuming as a criterion the level of indoor temperature decrease in residential rooms. The methodology of determining the overall index of heat-supply system reliability has been presented. The measure of heat-supply system reliability has been assumed as the scale/quantity of inadequate supply of heat power at a given state. Calculations have been carried out regarding the changeability of exterior conditions for one of the groups of customers – residential users. During the variant analysis a criterion determined by the level of outdoor temperature was assumed. This way, the multi-state characteristic of a heat-supply system, with reference to its reliability, has been taken into consideration.

Working out of the model of heat-supply system reliability requires taking its complexity, the extent of realization and its systematic treatment into consideration. The method can be used to evaluate the reliability in a heat supply system and to solve a lot of technical problems at the planning stage.

REFERENCES

1. Babiarz B.: *A reliability analysis of selected elements in heat supply systems*. Doctoral dissertation. Kraków 2002.
2. Babiarz B.: *An introduction to the assessment of reliability of the heat supply systems*. International Journal of Pressure Vessels and Piping, Volume 83, Number 4/2006, p. 230-235, Elsevier 2006.
3. Babiarz B., Rak J.: *The modelling of operational reliability in a heat supply system*. 4th International Conference of PhD Students, Miskolc 2003.
4. Barlow R. E., Clarotti C. A., Spizzichino F.: *Reliability and decision making*. Chapman & Hall 1993.