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Operational reliability of heat supply systems

Keywords

reliability, heat supply system, operation process

Abstract

The paper contains an analysis of the operational process of heat supply system with 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 the exploitation of heat-supply systems there have been distinguished five operational states, assuming as a criterion of the level of indoor temperature decrease in residential rooms. The method of modelling the operational 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 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. On the basis of the operational data for the heat supply system with two heat sources shortage quantities 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, directly determining practical possibilities of realising the aims of the system (tasks). Even if technical systems are perfect in functional sense, they become useless if the level of their reliability is not satisfactory-is lower than required [4]. The reliability of heat-supply system is closely connected with the reliability of its parts (sub-systems, structures), and determines the quality of completing tasks by the system after taking into consideration random changes of functional characteristics of the given system with the existence of computational external conditions [1]. 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, considering appropriate criteria, is an inseparable part of the analysis of an operational process of the system. Heat-supply systems may be included to relatively complex technical systems. Each of them constitutes a functional whole, divisible into sub-systems, structures and elements being connected with the climate, the environment and the demand for heat and characterised 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 load and efficiency, 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 operational reliability of heat-supply system units are presented considering the diversified operational ability of heating system.

2. Reliability states of operational process in a heat supply system

In the process of the exploitation of heat-supply systems there have been distinguished five operational states: (A), (B), (C), (D) i (E) (*Figure 1*), assuming as a criterion the level of indoor temperature decrease in residential rooms T_i [^{0}C] and the time of the lasting of interference in heat supply for consumers t_n[h], caused by failure [1], [3].

- *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

$T_{iA} = T_{io} = 20\ ^0C$ and there is no interference in a heat supply: $Q_A = Qn$, $Q_n[MW]$ – termed ordered heat power.

- *The state of partial permissible ability* (B) – state of permissible operational reliability, there are certain limitations in heat supply displaying a decrease in heated rooms temperature to T_i=15^{0}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: $\alpha_B Q_n \le Q_B < Q_n$.

- *The state of partial limited ability* (C) – state of limited operational reliability where considerable difficulties are observed, the ones connected with the necessity to make use of other heat sources for heating (electric energy, natural gas etc.), the heating equipment is only protected against freezing by maintaining a minimal temperature T_{iC} = 8^{0}C due to the supply of heat power: $\alpha_C Q_n \le Q_C < \alpha_B Q_n$.

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

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

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 described above operational states of heat supply system is given in *Figure 1.*

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 all 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 ^{0}C) and the times of their lasting.

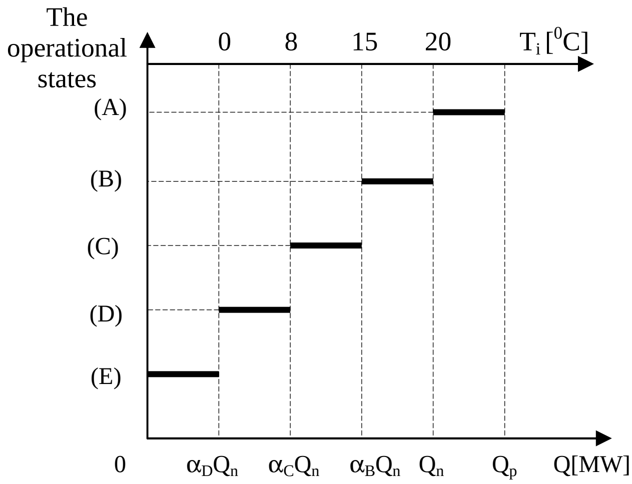

Figure 1. Classification of operational states of heating system depending on heat power Q[MW] and indoor temperature T_i [^{0}C]

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

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

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

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

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 cooling division wall in the building;
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

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

Analogically from the proportion of heat losses in the building residual factors: α_{Cx}, α_{Dx} have been determined:

α_{Cx} - factor of limited heat power decrease in state (C) for variant x;

α_{Dx} - factor of border heat power decrease in state (C) for variant x;

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

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

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

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

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

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

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

$$Q_{Ex} < \alpha_{Dx} Q_n \qquad (12)$$

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

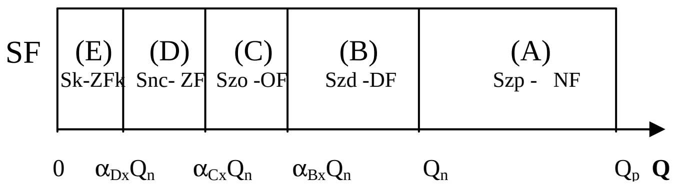

Figure 2. The operational states of heat supply system in the function of heat power

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*.

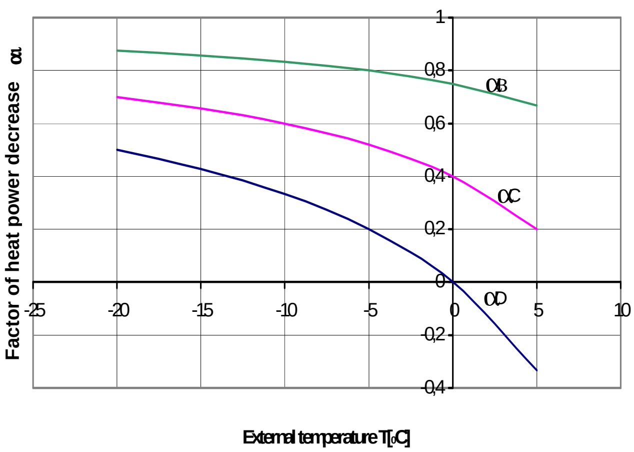

Figure 3. Relationship between factors of heat power decrease and external temperature considering changeable external conditions

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

3. The method of operational reliability assessment

Elements excluded in the decomposition process of a heat supply system as indivisible at a given stage of considerations are assumed to be treated as two-state and renewable elements.
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.

$$K_{el} = P(\mathrm{Sz}_{el}) = \frac{E(t_z)}{E(t_z) + E(t_n)} \qquad (13)$$

Stoppage index for element:

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

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 decrement parameters in specific operational conditions and time [2].
The measure of reliability is shortage quantity of heat power ΔQ_i in i-state for conditions describing variant x.

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

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;

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

when: φ_x - load factor for variant x;

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

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 losses balance for individual conditions.

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

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

$$K_u = 1 - U_u \tag{19}$$

4. En example of application of the worked out 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 [1], shortage quantities 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 the first variant determined by the level of external temperature T_e are presented in *Table 1.*

Heat power value for the first variant evaluate according to the (16) equals

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

because according to (17):

$\varphi_I = 1$

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

SF	UZC		P_i	Q_i [MW]		ΔQ [MW]	E(ΔQ) [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 situation when the heat source (UZC I or II) is in the state of complete ability (NF-Szp),
B - describes situation when the heat source (UZC) is in the state of partial permissible ability (DF-Szd),
C - describes situation when the heat source (UZC) is in the state of partial limited ability (OF-Szo),
D - describes situation when the heat source (UZC) is in the state of complete disability (DF-Snn),
E - describes situation when the the heat source (UZC) is in the state of disaster (ZF-Snk).

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

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

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

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

Calculations of the overall index of the heat-supply system reliability for every variants 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.*
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 ^{0}C, and a maximal value K_u = 0,999972 for variant VI, with external temperature T_e = + 5 ^{0}C.

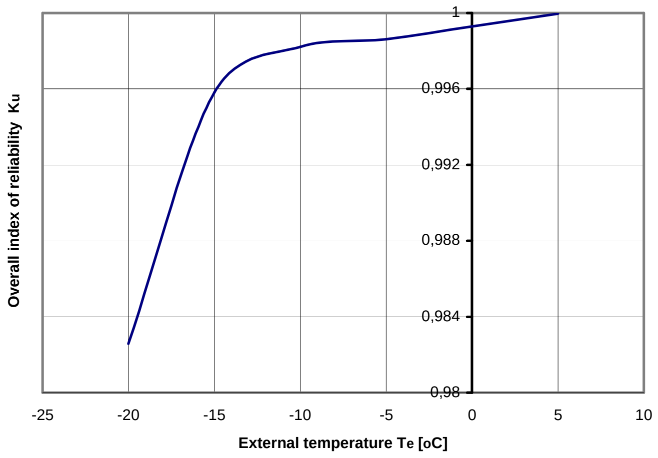

Figure 4. Dependence of overall index of heat-supply system reliability on external temperature

5. Conclusion

The specific character of the operation of heat-supply systems has been presented in this work. There has been worked out the model describing the functioning of heat-supply system structures in the aspect of reliability. In the process of the exploitation of heat-supply systems there have been distinguished five operational states, 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 there has been assumed a criterion determined by the level of outdoor temperature. This way the multi-state characteristic of a heat-supply system, with reference to its operational reliability, has been taken into consideration.

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

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