Michał PAJĄK
University of Technology and Humanities in Radom,
Faculty of Mechanical Engineering, Department of Thermal Technology
m.pajak@uthrad.pl

OPERATION AND SERVICE PROCESSES EXPRESSED IN THE TECHNICAL STATES SPACE OF A SYSTEM

Key words

Operational potential, Disposed amount of the operational potential, Modelling of operation and maintenance processes, The quality assessment of the operation and maintenance processes.

Abstract

During an operation phase, a technical system accomplishes goals, which were the reason of the system designing and creation. The main characteristics of a technical system's ability to accomplish these goals are the amount of the operational potential included in the system and the disposed amount of the potential. These values, expressed in the technical states' space, depend on the system's technical state and the definition of the ability and inability subspaces. During the operation and service processes, the technical states of the system changes. Therefore, in these processes, the change of the amount and the disposed amount of the operational potential takes place. In the paper, the changes of the amount and the disposed amount of the operational potential are expressed in the technical states' space of a system. Additionally, correlations of these changes are analysed. Next, in the space, the operation and service processes are expressed. Therefore, the changes of the amount and the disposed

amount of the operational potential, which happened during operation and service processes, could be observed. Based on presented description, the instructions of the efficient maintenance of the complex technical systems were formulated. At the end of the paper, the industrial research is presented. During this research, the operation and service processes of a real industrial system were analysed. As a result of the analysis, the changes of the disposed amount of the operational potential for these processes were calculated. Consequently, the quality of the system operation and servicing was estimated.

Introduction

The presented studies consider the technical states space described by the system features for which ranges of the acceptable values are equal to the ranges of suboptimal values. This is the strictly determined space. The space, described in detail in other publications of the author [1, 2], is a multidimensional one. The amount of its dimensions is equal to the amount of the identified cardinal features of the system. The method presented in the paper is a universal way of the analysis that can be conducted in n-dimensional spaces; however, in order to clarify the presentation, illustrations of the method elements are shown in two-dimensional space R^2. The example of the multidimensional inference can be found in [3].

The real operation position of the system s_R in such space is expressed as a point where coordinates of the point are equal to the instantaneous values of the cardinal features of the system. The point of the operation position can belong to the ability states' subspace S_Z or to the inability states' subspace S_{NZ} (Fig. 1).

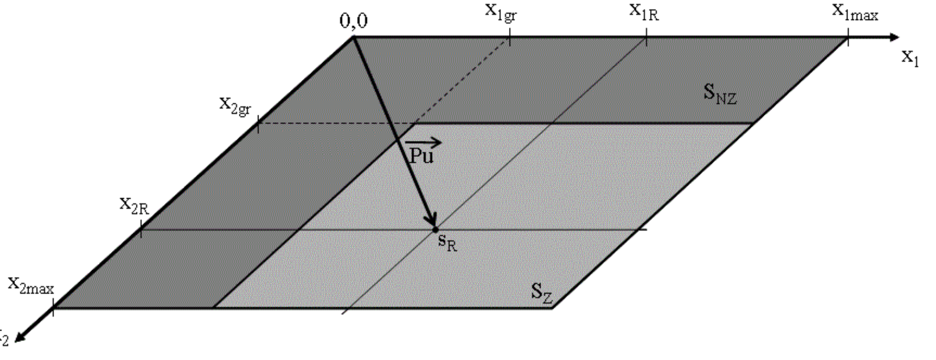

Fig. 1. Operational potential $\overrightarrow{Pu}$ included in a system in s_R state expressed in its technical states' space R^2

The operational potential included in the system is expressed in the space in the form of a vector. The starting point of this vector is the origin of the coordinates system, and the end point of it is the point of the real operation position of the system s_R. The amount of the operational potential included in the system is the length of the vector (Fig. 1).

The technical states' space of the system is Cartesian [4]; therefore, the considered length is calculated in the Euclidean metrics [5] according to the following formula (1):

$$Pu(s_R) = \sqrt{\sum_{i=1}^{n} (x_{Ri})^2} \tag{1}$$

Where: $Pu(s_R)$ – the amount of the operational potential included in the system in a state s_R, x_{Ri} – the value of a feature number i of the real operation position of the system s_R.

The vector between a point that belongs to the boundary of the ability states' subspace and the point of the real operation position of the system is an operational potential, which can be transformed to the effect of the system operation, included in the system in a moment t (Fig. 2). The length of this vector is equal to the disposed amount of the operational potential of the system and is calculated according to the following formula (2)

$$\delta Pu = \begin{cases} 0 \wedge s_R \in S_{NZ} \\ \sqrt{\sum_{i=1}^{n} (x_{Ri} - x_{BNZDi})^2} \wedge s_R \in S_Z \end{cases} \tag{2}$$

Where: S_{NZ} – the ability states' subspace, S_Z – the inability states' subspace, x_{BNZDi} – the value of a feature no. i of the point s_{BNZD} which belongs to the boundary of the ability states' subspace.

Implementation of the operational potential definition introduced above takes into consideration the multidimensional character of the potential, because its value is calculated using the changes of the values of all cardinal features of the system (the length of the vector in multidimensional space). Additionally, thanks to the implementation, the definitional and interpretational ambiguity arising from the customary terms and measures used during the description

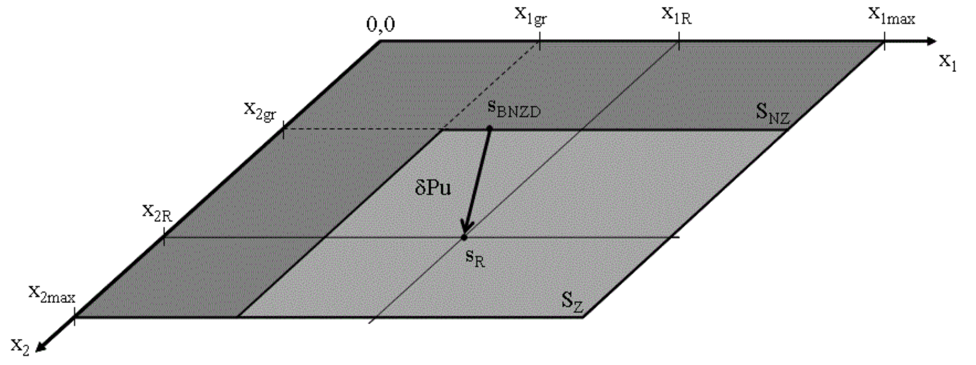

Fig. 2. Operational potential that can be transformed to the effect of the operation $\overrightarrow{\delta Pu}$ included in a system in s_R state expressed in its technical states' space R^2

process of the operational potential are solved. The detailed analysis of the method in the context of the other definitions and calculations of the operational potential is presented in the author's publication [6].

1. The changes of the operational potential during the maintenance and operation phase

During the operation processes executed by the technical system, the system is exposed to the impact of wearing factors. The factors are dependent on or independent from the system operation [7]. The influence of the factors results in the changes of the values of the system's cardinal features [8]. Therefore, the operation position of the system changes during the operation and maintenance phase. The operation position of the system is expressed by the point defined by the coordinates equal to the instantaneous values of the cardinal features of the system. Thus, the process of the changes of the operation positions of the system can be expressed in the form of the trajectory where each point is a representation of the system state for the time moment *t*, $t \subset [t_1,\ t_2]$ [9, 10, 11].

Stating the amount of the operational potential of the system (1) for the starting point of the trajectory $s_1 = s(t_1)$ and ending point of the trajectory $s_2 = s(t_2)$, it is possible to calculate the change of the amount of the operational potential during the considered operation or service process as a length of the vector of the operational potential change (3) (Fig. 3).

$$\Delta Pu = \left|\overrightarrow{\Delta Pu}\right| : \overrightarrow{\Delta Pu} = \overrightarrow{\Delta Pu}(s_1) - \overrightarrow{\Delta Pu}(s_2) \tag{3}$$

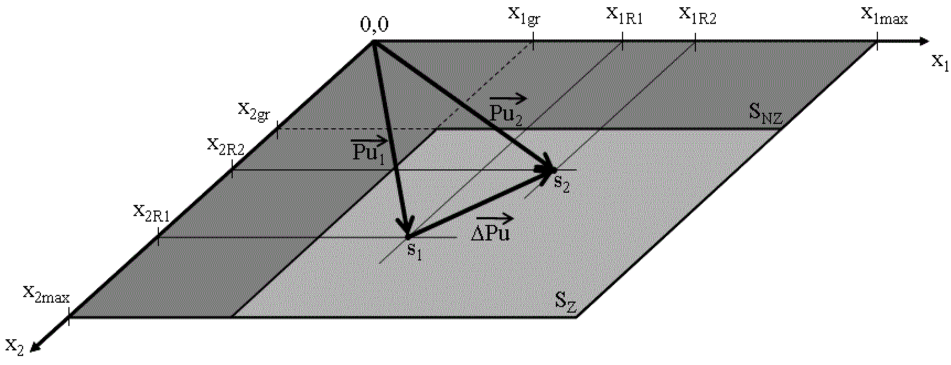

Fig. 3. The change of the operational potential during operation or service process expressed in the technical system states space R^2

Assuming the selected boundary state s_{gr} as a point with respect to which the disposed amount of the operational potential is defined, this amount can be calculated for the starting and ending points of the analysed trajectory. The difference between vectors designated for the starting and ending points is a vector of the change of the operational potential disposed amount of the system and its length is the change of this amount $\Delta\delta Pu$ (4) (Fig. 4).

$$\Delta\delta Pu = \left|\overrightarrow{\Delta\delta Pu}\right| : \overrightarrow{\Delta\delta Pu} = \overrightarrow{\delta Pu}(s_1) - \overrightarrow{\delta Pu}(s_2) \tag{4}$$

Where: $\Delta\delta Pu$ – the change of the disposed amount of the operational potential.

It should be noticed that, for points not belonging to the inability states' subspace, the operational potential vector is a sum of the operational potential vector designated for the selected boundary state s_{gr} and the vector of the disposed amount of the operational potential designated with respect to this boundary point (5) (Fig. 5).

$$\forall s_R \notin S_{NZ} : \overrightarrow{Pu}(s_R) = \overrightarrow{Pu}(s_{gr}) + \overrightarrow{\delta Pu}(s_R) \tag{5}$$

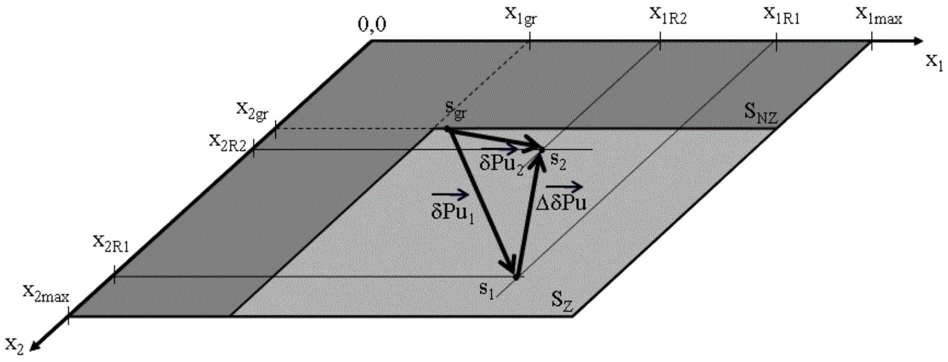

Fig. 4. The change of the disposed amount of the operational potential expressed in the technical system states space R^2

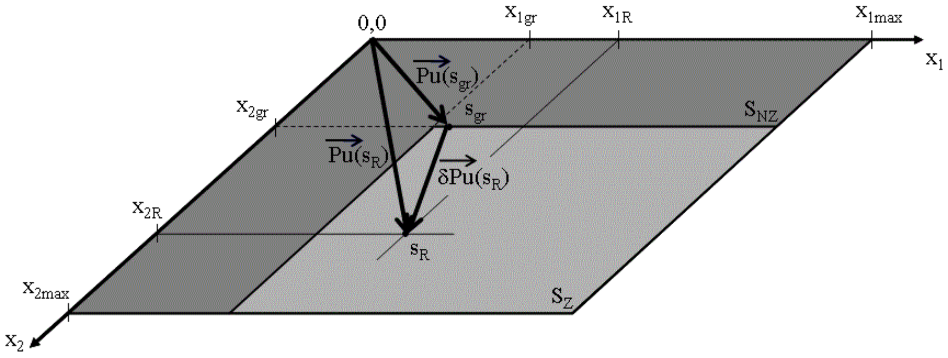

Fig. 5. The operational potential $\overrightarrow{Pu}(s_R)$ expressed in the technical system states' space R^2 as a sum of the operational potential of a boundary state $\overrightarrow{Pu}(s_{gr})$ and a vector of the disposed amount of the operational potential $\overrightarrow{Pu}(s_R)$

This sum is a constant value for the specified real operation position of the system. Therefore, selecting for the calculation a boundary point for which the amount of the operational potential is the smallest one, the biggest disposed amount of the operational potential is obtained. This state is defined as the optimal boundary state.

Definition 1: *Optimal boundary state is a state which belongs to the boundary of the ability states' subspace and for which the amount of the operational potential included in the system is minimum.*

In case of the operation or service process executed in such way that its starting and ending points does not belong to the inability states' space, taking into account Formula 5, the vector equation (6) can be shown as follows:

$$\begin{aligned}&\overrightarrow{\Delta Pu} = \overrightarrow{\Delta Pu}(s_1) - \overrightarrow{\Delta Pu}(s_2) = \\ &\overrightarrow{Pu}(s_{gr}) + \overrightarrow{\delta Pu}(s_1) - \overrightarrow{Pu}(s_{gr}) - \overrightarrow{\delta Pu}(s_2) = \overrightarrow{\Delta\delta Pu}\end{aligned} \tag{6}$$

Analysing Formula 6, one can conclude that, for operation or service processes executed beyond the inability states' subspace, the change of the amount of the operational potential is equal to the change of the disposed amount of the operational potential during the process execution.

2. Operation and service processes expressed in the technical states' space of the system

The most important groups of the processes executed in the technical system are the operation and service groups. Both of them are expressed in the technical states' space of the system in the form of the trajectory of its operation position. In the Figure 6, the representations of the operation process and the service process executed by replacement, in the technical states' space of the system R^2, are presented. For the same processes, the flow of the function of the operational potential consumption is presented in the Figure 7 [12].

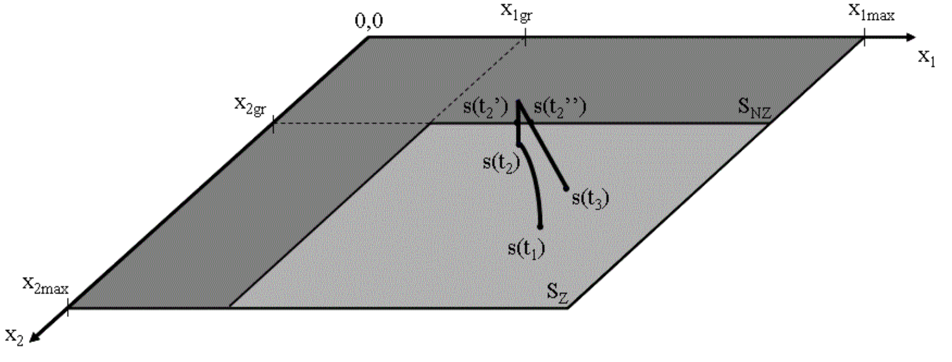

Fig. 6. Exemplary operation and service processes expressed in the technical system states' space R^2

In the figure (Fig. 6), the operation process runs between time moment t_1 and time moment t_2. The service process begins in the last moment of the operation process t_2 and runs until its ending moment t_3. It was stated that whole operation process is executed beyond the inability states' subspace, which means that, for this kind of process, the change of the operational potential amount included in the system equals to the change of the disposed amount of the potential.

The service process is executed beyond the inability states' subspace between time moment t_2 and time moment t'_2 and between time moment t''_2 and time moment t_3, while in the period of time $(t'_2,\ t''_2)$ runs in this subspace. For time moments t, $t \in [[t_2, t'_2] \cup [t''_2, t_3]]$, the change of the operational potential amount included in the system equals the change of the disposed amount of the potential. For time moments t, $t \in (t'_2, t''_2)$, the change of the amount of the operational potential included in the system can be different than zero, but the disposed amount of the operational potential and the change of this amount are equal to zero.

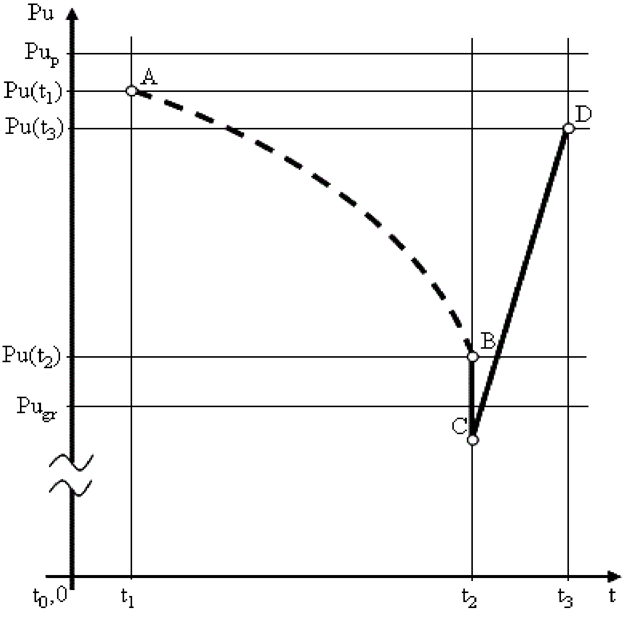

Fig. 7. Changes of the amount of the operational potential during an operation process (dashed line) and service process (solid line)

Expressing the operational potential term and its changes in the technical states' space of the system, it can stated that, in this space, the operational potential field is forming. The field is a homogeneous, central, vector potential field [13] of sphere shaped equipotential surfaces [14]. It means that each point of the field is assigned a vector lying on a straight line that connects this point and the central point of the field and that the intensity of the field for each point of the equipotential surface has the same value [15]. In such a field, the change of the amount of the potential is independent from the trajectory and depends on the starting and ending position. As already mentioned, in case of the operation processes, the change of the amount of the operational potential included in the system equals the change of the disposed amount of this potential. Thus, the following definition can finally be made:

Definition 2: *The change of the disposed amount of the system* $\Delta\delta Pu$ *during the operation processes execution is independent from the trajectory of the system operation position but depends on its starting and ending location.*

As far as the service processes with start time determined in advance are concerned, the disposed amount of the operational potential that can be transformed into the effects of the system operation is maximum only if the operation and service processes are executed according to the maintenance strategy by controlled consumption of the operational potential [16]. According to this strategy, to accomplish the operation and service processes in an efficient way, it is necessary to control the intensity of the operation process to obtain the minimum value of the disposed amount of the operational potential in the determined time moment t_2 and keep the system in the ability state. The control of the intensity of the operation process in the technical states' space consists in the change of the trajectory of the point of the system operation position to force the location of the point as near as possible to the boundary state in the last moment of the considered process (Fig. 8 – dashed line).

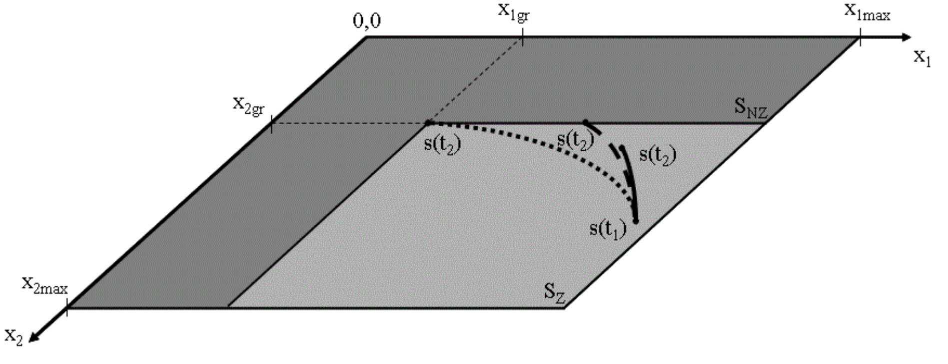

Fig. 8. Exemplary operation process executed without the operational potential consumption control (solid line), executed with the operational potential consumption control (dashed line), and executed with the operational potential consumption control when all system features are renewable (dotted line)

Analysing the considered operation process in the technical states' space of the system, it can be stated that, as far as all the system features are renewed during the service process, in order to obtain the maximum disposed amount of the operational potential transformed into the effects of the system operation, it is necessary to form the trajectory of the operation process to make the location of the operation position of the system for the latest moment of the process as near as possible the optimal boundary state (Fig. 8 – dotted line).

The operation and maintenance processes of the technical system are modelled using different types of the mathematical models. However, in case of the maintenance management of the complex crucial technical system of strategic importance, they are not sufficient. The detailed analysis of this problem can be found in the author's paper [17].

3. The analysis of the changes of the operational potential of the real industrial system

During the industrial research carried out, the technical system of the OP-650k-040 boiler was analysed. As a result of the research, four deviations were chosen as cardinal features – the determinants of the technical states' space of the analysed boiler. The deviations are presented in the following list:

- *q3* – the deviation which occurs as a result of the reduced temperature of the reheated steam,
- *q4* – the deviation which occurs as a result of the pressure loses in the secondary reheater of the steam,
- *q5* – the deviation which occurs as a result of the injections of water to the secondary reheated steam,
- *q8* – the deviation, which occurs as a result of the reduced efficiency of the boiler operation.

Additionally, it was stated that, from the point of view of the technical state, the range of the acceptable values is equal to the range of the suboptimal values for each of the selected features. Thus, the features are the strictly defined, and they form the strictly determined technical states' space of the system.

Based on the measurements registered during the research, the instantaneous values of the chosen deviations were calculated. Afterwards, implementing polynomial approximation, the time functions of each deviation were formulated. Next, the derivative of each function was calculated. The sign of each derivative was positive, which means that the functions are increasing in the analysed domains. For each function, its minimum and maximum values were also calculated. On this basis, it was confirmed that execution the service processes decreases the values of the deviations. This means that all selected cardinal features of the system are renewed during the service processes.

According to the description presented above, the optimal boundary point of the considered system was designated. Its coordinates are equal to the maximum values occurring at the end of the operating periods of the boiler just before the service processes start and are respectively 16.8873, 41.1034, 131.9413, and 398.9218 [kJ/kWh]. In the next step, for the starting and ending state of each examined operation process, the disposed amount of the operational potential was calculated according to Formula 2 with respect to the optimal boundary point. The changes of the disposed amount of the operational potential during the same operation processes were also calculated (4). The results of the calculations are presented in Table 1.

Table 1. The changes of the disposed amount of the operational potential – operation processes

No.	The disposed amount of the operational potential at the beginning of the operation process	The disposed amount of the operational potential at the end of the operation process	The change of the disposed amount of the operational potential	The percentage of the disposed operational potential utilisation
	[kJ/kWh]	[kJ/kWh]	[kJ/kWh]	[%]
1	497.2604	321.7175	175.5429	35.30201
2	825.47	54.29092	771.1791	93.42303
3	720.2842	368.7513	351.5329	48.80475
4	467.817	70.8926	396.9244	84.84608
5	826.173	13.96614	812.2068	98.30954
6	636.8958	225.2122	411.6836	64.63908
7	516.8694	122.4285	394.4409	76.31346
8	787.5193	248.9911	538.5283	68.38286
Mean value			481.5	71.25

In accordance with the theory described above, the disposed amount of the operational potential included in a system at the beginning of the operation process is interpreted as a maximal amount of this potential that can be transformed in the system operation. After having calculated the change of the disposed amount of the operational potential during the considered operation process, it is possible to refer it to the disposed amount of the operational potential included in a system at the beginning of the operation process, designating the quality of the system operation (7) in this way.

$$Q_u = \frac{\Delta \delta P_u}{\delta P_u(s_1)} \cdot 100\% \tag{7}$$

Where: Q_u – the quality of the system operation [%], $\Delta\delta Pu$ – the change of the disposed amount of the operational potential, $\delta Pu(s_1)$ – the disposed amount of the operational potential included in a system at the beginning of the operation process.

The calculated quality of each analysed operation process was presented in Table 1. In the table, the mean value of the change of the disposed amount of the operational potential and the mean quality of the system operation were also presented.

Thanks to the method described in this paper, one can state that the operation processes executed in the technical system of the OP-650k-040 boiler are performed with mean quality slightly over 71%. Taking into account the existence of the processes for which the quality of the operational potential utilization is above 90%, the conclusion can be formulated that it is possible to increase the quality of the concerned system operation.

Similarly, the disposed amount of the operational potential at the beginning and the end of each analysed service process was calculated. The calculations were carried out with respect to the optimal boundary state according to Formula 2. The results of the calculations are presented in Table 2. In the table, the change of the disposed amount of the operational potential during the service processes calculated according to Formula 4 can also be found.

Additionally, in the case of analysed service processes, it was assumed that the percentage of the disposed amount of the operational potential renewed during the concerned process referred to the disposed amount of the operational potential included in a system at the end of the service process is a measure of the quality of the system renovation. The measure was calculated according to Formula 8, and it is presented in Table 2.

$$Q_o = \frac{\Delta \delta P_u}{\delta P_u(s_2)} \cdot 100\% \qquad (8)$$

Where: Q_o – the quality of the system renovation [%], $\Delta\delta Pu$ – the change of the disposed amount of the operational potential, $\delta Pu(s_2)$ – the disposed amount of the operational potential included in a system at the end of the service process.

Table 2. The changes of the disposed amount of the operational potential – service processes

No.	The disposed amount of the operational potential at the beginning of the service process	The disposed amount of the operational potential at the end of the service process	The change of the disposed amount of the operational potential	Percentage of the renewed disposed amount of the operational potential
-	[kJ/kWh]	[kJ/kWh]	[kJ/kWh]	[%]
1.	321.7175	670.7211	349.0036	52.03409232
2.	54.29092	535.4239	481.1329	89.86019741
3.	368.7513	631.4707	262.7195	41.60437615
4.	13.96614	830.4075	816.4414	98.31815872
5.	225.2122	807.3741	582.1619	72.10559841
6.	122.4285	556.3788	433.9503	77.99548387
Mean value			487.57	71.99

Analysing the obtained values, we can conclude that service processes executed in the technical system of the OP-650k-040 boiler were performed with mean quality near 72%. Simultaneously, the quality of the renovation, in case of some service processes, is about 90%. On this basis, the conclusion was formulated that it is possible to increase the quality of the system renovation.

Summary

It should be stressed that, thanks to the theoretical studies described in this paper and their implementation in case of a real industrial system, it was possible to formulate the following list of conclusions:

- The change of the amount of the operational potential during the operation process equals to the change of the disposed amount of this potential.
- The change of the disposed amount of the operational potential $\Delta\delta Pu$ during the operation process is independent of the trajectory of the system's operational position but dependent on its start and end location.
- To accomplish the operation and service processes in an efficient way, it is necessary to control the intensity of the operation process to obtain the minimum value of the disposed amount of the operational potential in the determined time moment t_2 and keep the system in the ability state.
- As far as all the system features are renewed during the service process, in order to obtain the maximum disposed amount of the operational potential transformed into the effects of the system operation, it is necessary to form the trajectory of the operation process to make the location of the operation position of the system for the latest moment of the process as near as possible the optimal boundary state.
- Thanks to the implementation of the theory presented in this paper, it is possible to determine the quality of the complex technical system operation and the quality of the system renovation.
- The operation processes executed in the technical system of the OP-650k-040 boiler are performed with a mean quality slightly over 71%; however, the existence of the processes for which the quality of the operational potential utilization is above 90%, which means that it is possible to increase the quality of the concerned system operation.
- The service processes executed in the technical system of the OP-650k-040 boiler are performed with mean quality near 72%; however, simultaneously, the quality of the renovation, in case of several service processes, is about 90%, thus it is possible to increase the quality of the system renovation.

References

1. Pająk M.: The space of a feature of a complex technical system. Scientific Problems of Machines Operation and Maintenance, 2/2010, ITeE – PIB, Radom 2010, pp. 31–41.
2. Pająk M.: Types of the states space of complex technical systems. Journal of KONES Powertrain and transport vol. 18 No. 3, Warsaw 2011, pp. 323–331.
3. Pająk M.: The technical states' space in the modelling process of operation tasks of a complex technical system. Maintenance Problems, 1/2014, ITeE – PIB, Radom 2014, pp. 15–33.
4. Muszyński J.: Analiza matematyczna cz.I. Publishing House of Warsaw Polytechnic, Warszawa 2000.
5. Dorst L., Fontijne D., Mann S.: Geometric Algebra for Computer Science. Elsevier 2007.
6. Pająk M.: Operational Potential of a Complex Technical System. Maintenance Problems, 4/2015, ITeE – PIB, Radom 2015, pp. 99–113.
7. Pająk M., Muślewski Ł.: Rozmyty model oceny jakości działania złożonego systemu eksploatacji. Maintenance Problems 3/2005, ITeE – PIB, Radom 2005, pp. 213–225.
8. Muślewski Ł., Woropay M., Pająk M.: Zastosowanie elementów logiki rozmytej w ocenie jakości działania złożonych systemów eksploatacji. Scientific conference: Budowa i eksploatacja obiektów technicznych w teorii i praktyce. Pieczyska 2005, pp. 64–74.
9. Pająk M., Muślewski Ł.: Computerisation of systems operation quality assessment. 10th International Conference Computer systems aided science, industry and transport Transcomp, Zakopane 2006, pp. 147–153.
10. Smalko Z.: Podstawy eksploatacji technicznej pojazdów. Publishing House of Warsaw Polytechnic, Warszawa 1998.
11. Woropay M., Muślewski Ł., Pająk M.: Fuzzy model to evaluate the system operation quality. 9th Scientific Seminar on Developments in Machinery Design and Control. Book of Extended Abstracts, Vol. 7, Bydgoszcz – Muszyna 2005.
12. Pająk M.: The modification of the amount of operational potential during the exploitation phase of a complex technical object. Scientific Problems of Machines Operation and Maintenance 1/2009, ITeE, Radom 2009, pp. 37–49.
13. Weyna S.: Rozpływ energii akustycznych źródeł rzeczywistych. WNT, Warszawa 2005.
14. Barlik M., Pachuta A.: Geodezja fizyczna i grawimetria geodezyjna. Teoria i praktyka. Publishing House of Warsaw Polytechnic, Warszawa 2007.
15. Massalski J., Massalska M.: Fizyka dla inżynierów. WNT, Warszawa 2006.

16. Pająk M., Woropay M.: Maintenance Strategy by Controlled Consumption of Operational Potential. Journal of KONES Powertrain and transport, Vol. 16 No. 4, Warsaw 2009, pp. 367 – 374.
17. Pająk M.: The Analysis of Usefulness of Operational Potential Consumption Models to Control Complex Technical Systems Maintenance. Journal of KONES Powertrain and transport, Vol. 17 No. 2, Warsaw 2010, pp. 387–395.

Opis procesów eskploatacyjnych w przestrzeni stanów technicznych systemu

Słowa kluczowe

Potencjał użytkowy, ilość dysponowana potencjału użytkowego, modelowanie procesów eksploatacyjnych, ocena jakości procesów eksploatacyjnych.

Streszczenie

Podstawowymi wielkościami charakteryzującymi zdolność systemu eksploatacyjnego do realizacji zadań, do wypełnienia których został stworzony jest ilość zawartego w nim potencjału użytkowego i ilość dysponowana tego potencjału. Wielkości te wyrażone w przestrzeni stanów technicznych zależą od stanu technicznego systemu i definicji obszarów zdatności i niezdatności. Ponieważ w trakcie przeprowadzania procesów użytkowania i odnowy stan techniczny ulega zmianie, to zmieniają się również ilość potencjału użytkowego i jego ilość dysponowana. W opracowaniu odwzorowano zmiany ilości potencjału użytkowego i ilości dysponowanej tego potencjału w przestrzeni stanów technicznych systemu, analizując ich wzajemne powiązania. Na tej podstawie zdefiniowano pojęcie stanu granicznego optymalnego. Następnie w przestrzeni tej odwzorowano procesy użytkowania i odnowy, obrazując zmiany ilości dysponowanej potencjału użytkowego zachodzące w trakcie realizacji tych procesów. Bazując na wprowadzonym opisie, sformułowano wskazania mające na celu racjonalizację eksploatacji złożonych systemów technicznych. W końcowej części opracowania opisano badania eksploatacyjne przeprowadzone na rzeczywistym systemie przemysłowym. W trakcie tych badań obliczono zmiany ilości dysponowanej potencjału użytkowego rozważanego systemu technicznego zachodzące w procesach użytkowania i odnowy. Na tej podstawie określono jakość użytkowania i odnawiania analizowanego systemu eksploatacyjnego.