STABILITY OF SYSTEMS IN EXTREME OPERATING CONDITIONS

ANTON MAZURENKO[1], ANTON PANDA[2,4], OLEKSANDR KLYMCHUK[1], GANNA POZDNIAKOVA[1], ANATOLIY PUSTOVIT[1], JAN VALICEK[3,4], MARTA HARNICAROVA[3,4]

[1]Department of Energy, Odesa Polytechnic National University, Odesa, Ukraine

[2]Faculty of Manufacturing Technologies with a seat in Presov, Technical University of Kosice, Presov, Slovakia

[3]Slovak University of Agriculture in Nitra, Institute of Design and Engineering Technologies, Faculty of Engineering, Slovakia

[4]Institute of Technology and Business in Ceske Budejovice, Faculty of Technology, Department of Mechanical Engineering, Ceske Budejovice, Czech Republic

DOI: 10.17973/MMSJ.2025_11_2025037

e-mail: anton.panda@tuke.sk

This study examines the problems of the district heating systems current state. The causes of extreme operating conditions of district heating systems in Ukraine and in the Eastern European region have been analyzed. Considered are the main factors influencing the district heating systems stability in extreme conditions. Promising approaches are proposed to increase the reliability of district heating systems operation. It is found that the use of electricity generation reserve sources in cogeneration mode with simultaneous release into system of utilized heat provides significant savings in costs for their operation. It is proven that the district heating system readiness for proper operation should be assessed by the number of the heating network, thermal energy source and thermal energy consumers expected readiness hours in relation to the heating season duration. It is shown that the consumption efficiency coefficient does not directly correlate to the generation efficiency and heat supply to consumers but influences the entire heating system efficiency.

KEYWORDS

energy equipment reliability, system stability, district heating systems, cogeneration plants.

INTRODUCTION

Ensuring the safety and reliability of the municipal heat and power industry district heating sector functioning is an important step towards the restoration, more sustainable development and prosperity of the country in the future [European Energy Security Strategy 2014]. Here the task of developing ways to ensure the reliable and sustainable operation of district heating systems in modern conditions is becoming an urgent one, which will require the modernization of critical infrastructure facilities [Fournier 2023, Sagova 2025].

Heat supply is an important element of the civilian population's life support systems as well as a crucial precondition for reliable function of some types of industrial and agricultural production in most European countries, including Ukraine [Law of Ukraine 2017]. For reliable operation of heat supply systems under extreme conditions, necessary is to be able of ensuring the heat supply system integrity, and this aspect is tightly linked with a number of specific problems which solution requires a comprehensive approach [Cabinet of Ministers of Ukraine 2017].

The reasons for extreme operating conditions in the Eastern European region may vary as follows:

- too low winter season temperatures, strong winds, abundant precipitation and other climatic peculiarities;
- technical problems due to wear and tear of equipment when its resource is worked out;
- socio-economic factors associated with high costs borne by local communities or state budgets, primarily in situations when a significant increase in fuel costs for heat production takes place;
- when about Ukraine, there are such additional influencing factors as: wartime problems, which include: damage to infrastructure due to hostilities, interruptions in the supply of fuel, water and electricity supply,

difficulties in accessing repair work in the war-affected areas, and others.

Ensuring stable power supply to heating boiler houses during power outages is an important technical and economic task. The heating boiler houses' power outages cause interruptions in heat production for consumers, at the same time being the reason of heat supply systems cooling and failure of technological process elements.

Individual heating systems, which are most common in rural areas or in suburban settlements, are the most resistant to extreme conditions due to the possibility of using different types of fuel, availability of a closed heat carrier system, and the lack of the need, in most cases, for a stable power supply [Mazurenko 2014a].

MATERIALS AND METHODS

In urban conditions, the centralized heat supply systems are the main sources of heat for apartment buildings, as well as for administrative and industrial buildings. Therefore, we shall consider the main factors which under such circumstances affect the heat supply system stability in extreme operating conditions; in this study we propose to express that criterion through the stability coefficient - К_V . Existing estimates of the heat supply systems reliable operation: the probability of failure-free operation P, the readiness coefficient and survivability [7], were developed in peacetime, therefore they do not take into account the possibilities of system elements passive (physical) protection, and also do not represent the content of these indicators' components.

The stability coefficient is formed based on a number of separate indicators:

$$К_V = К_F \cdot К_W \cdot К_E \cdot К_B \cdot К_L \cdot К_S \cdot К_T \cdot К_D \quad (1)$$

Let's analyze the content of each of that coefficient's components.

$К_F$ - coefficient of fuel supply reliability. Its highest value shall be reached when it is possible to use boiler houses of various types and operated sources. In addition, key importance here is tribute to the protection of gas pipelines, liquid fuel tanks or solid fuel storage conditions.

$К_W$ - coefficient of water supply reliability. Unlike individual heating systems, boiler houses require constant replenishment of heat supply systems with heat carrier due to its losses during heat generation in the boiler house, at heat transport in the network, as well as at consumers' equipment. With qualified operation of all these elements, especially in case of new heat mains using pre-insulated pipes, the need for replenishment is minimal and losses can be compensated for by reserve stocks.

$К_E$ – as practice while military operations shows, the stability of power supply systems, namely the characteristic this coefficient reflects, is quite vulnerable, both under impacts affecting the system and at local impacts. The introduction of backup power generation (both autonomous and in cogeneration mode) [Klimenko 2018, Panda 2014 & 2021, Nahornyi 2022, Sukhodub 2018 & 2019, Harnicarova 2019, Pandova 2020], immediately in boiler houses allows preventing the long-term shutdowns of heat generation in the event of external power sources' and the power grid accidents. At present, almost all urban boiler houses in Ukraine are equipped with backup sources of power generation to meet their own needs, which has significantly increased the reliability of heat supply systems.

$К_B$ – reliability coefficient of boiler house equipment. An important role in this parameter is played by the exhausted resource of the main and auxiliary equipment, as well as the availability of the boiler house installed capacity reserve secured with the backup boiler units.

Кт - coefficient of reliability of the heat carrier transport system from the boiler house to consumers; it largely depends on the type of heat networks: open, channel type or channelless. Open networks are the most vulnerable, but they are the most accessible for damage detection and their restoration. The use of channelless pre-insulated pipes where the impulse damage detection system is used, also allows getting an efficient solution to this problem.

$К_L$ - coefficient of heat supply system elements protection. Passive protection methods can play a significant role in increasing the heat supply stability, but they usually require significant financial costs, as well as certain time for their implementation [Panda 2020 & 2022]. For example, the construction of underground boiler rooms in mining, catacombs, or even powerful reinforced concrete shelters can significantly increase the stability of heat generation and heat carrier transport systems.

$К_S$ - coefficient of heat supply system elements protection. Passive protection methods can play a significant role in increasing the heat supply stability, but they usually require significant financial costs, as well as certain time for their implementation. For example, the construction of underground boiler rooms in mining, catacombs, or even powerful reinforced concrete shelters can significantly increase the stability of heat generation and heat carrier transport systems.

With this approach, quite promising in our opinion shall be the introduction of heat generation realized through the use of modular microreactors (MMR), which, with their sufficient thermal power production, have small dimensions, being at the same time reliable, safe, and most importantly, do not require constant consumption of organic fuel, since they use nuclear fuel, which is reloaded after 8-10 years of operation elapsed. At that, the fuel component cost, which is usually the largest value when using traditional types of fuel, is several times lower when operating such a boiler house.

Additional use of renewable energy sources allows to increase the efficiency of thermal generation [Klymchuk 2020]. And the heat pump systems introduction will allow both to increase energy independence and improve the level of reliability of centralized heating supply [Mazurenko 2014b].

$К_T$ – this coefficient reflects the presence in the heat supply system of a sufficient number of personnel who can ensure a qualified level of equipment operation, as well as prompt performance of repair and restoration works.

To increase this coefficient, it is possible to use the heat supply facilities system automatic control with dispatching.

$К_D$ - the heat supply systems duplication coefficient, whose value depends on the presence of a unified system of boiler houses, which, in the presence of backup heat networks, can partially or even completely compensate for the impossibility of operating one of the boiler houses in that system. This coefficient is primarily contributed to by roof boiler rooms, basement boiler rooms for a group of clients, individual heat supply points, etc.

Determining the specified coefficients is a rather difficult task, since they depend on many both external independent and controlled factors for specific systems [Duhancik 2024]. The most accurate one can be considered the method of collecting a large amount of data and those data statistical analysis concerning various heat supply systems' failures in the corresponding operating conditions.

Here the methodology of professional expert assessments also should never be ignored. A significant number of such expert assessments can serve in an objective indicator of both the heat supply system's reliability and stability in extreme conditions.

The operating data of one of the large district boiler houses in Odessa city during 2023, which are presented in Table 1 and Fig. 1, indicate that the maximum electricity consumption period falls in December - March. In November, the boiler house does not operate for a full month, so these data are not indicative, and from April to October, its electricity consumption makes only a few percent of the maximum, as it is used only for repair work, lighting, etc.

Table 1. District boiler house operation data

Boiler house parameters	Months of the heating season 2023				
	January	February	March	November	December
Thermal energy production, Gcal	24400	22420	18940	11700	24920
Electricity consumption, kWh	1036620	979023	1053810	486500	980178
Average power consumption of the boiler house kW	1 393	1 457	1 416	675,7	1 317

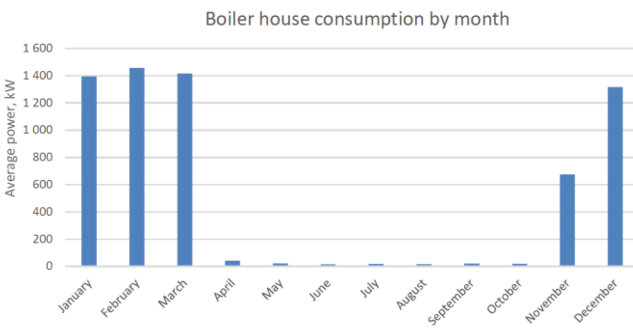

Figure 1. Electrical energy power consumption by the boiler house one year round

The largest average monthly power supply for heating needs in this case is 1457 kW in February. When installing an autonomous power generation system, for example, based on a gas turbine [Radosavljevic 2018] it is possible to provide not only backup (or even basic) power supply to the boiler house, but at the same time, when installing a conventional gas-water heater behind the turbine, obtain a significant amount of heat.

Fig. 2 shows the initial parameters and the performance calculation of such a gas turbine with cogeneration. It should be noted that the use of backup sources of electricity generation in cogeneration mode with simultaneous release of utilized heat provides significant savings in costs for those backup sources operation [Atanasoae 2020] and also allows maintaining the survivability of heat supply systems even when the main heat-generating equipment (boiler) is out of order.

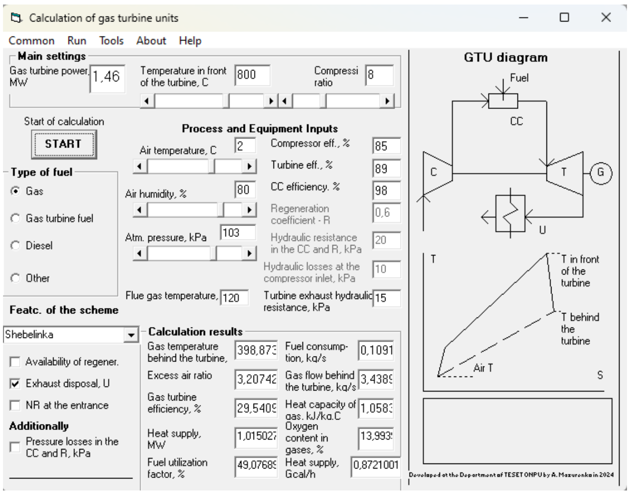

Figure 2. View of the GTU scheme with exhaust gas heat recovery and the result of its calculations in the developed program

When installing local electricity generation capacity in excess of that required for operation, or when there is a surplus of electricity generation comparing to that required for the system's own needs, it is possible and advisable to use this surplus in extreme conditions for electric heating of network water under extremely low ambient temperatures including through the use of heat pump systems [Klymchuk 2018] and thus to ensure the system survivability for the period of restoration works (Fig. 3).

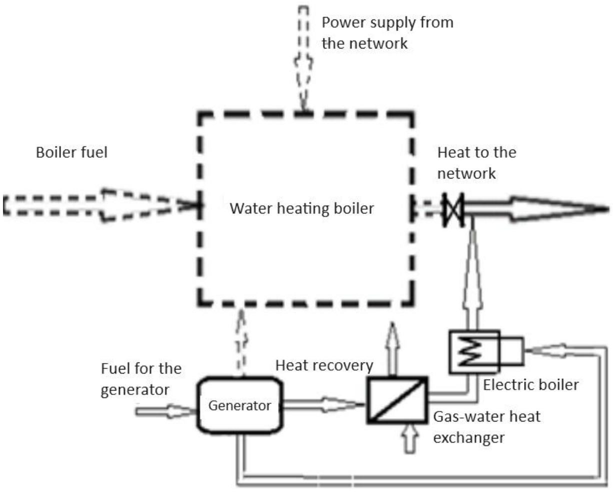

Figure 3. Scheme of a boiler room with a backup electric generator in cogeneration mode thus ensuring the system survivability due to electric heating of network water

Of course, it is necessary to try to ensure the fulfillment of the requirements of State standards developed in peacetime, even in today's real, sometimes extreme conditions of hostilities. Thus, in accordance with the actually existing norms, heat supply systems must for a given time provide consumers with reliable heat supply, characterized by three main indicators:

- degree of failure-free operation probability P;
- readiness(availability) coefficient Kr;
- survivability S.

The minimum permissible values of the failure-free operation probability P are recommended to be taken for indicators of:

- the heat energy source PS = 0.97;
- the heat network PN = 0.9;
- the heat energy consumer PU = 0.99,

i.e. for the heat supply system as a whole.

The heat supply system readiness for proper operation should be determined by the number of hours of the heat energy source, heat network and heat energy consumers expected readiness assessed in relation to the heating season duration. The minimum permissible value of the heat supply system readiness for proper operation Кg is taken as 0.97.

RESULTS

The currently valid standards also establish indicators of the heat supply systems survivability, which assess the possibility of restoring the heat supply systems operability after accidents caused by climatic and technogenic factors, which can lead mainly to freezing of the system and destruction of its individual components and pipelines, but these Standards do not take into account the need to protect them from their possible destruction in connection with military operations.

Even in extreme conditions, the issue of heat generation efficiency remains relevant, since the main fuel used for boiler houses nowadays is a rather expensive type of fuel, the gas, and for backup electric generators there is an alternative between gas or its no less expensive competitor the liquid fuel.

According to European standards, it is generally accepted that the heat supply system overall efficiency coefficient (OEC) K is:

$$K = 65 + 3 \cdot log(Q) \quad (2)$$

where log(Q) is the decimal logarithm of the nominal capacity of the boiler house Q. The thermal capacity of the boiler is given in kW. Heat supply efficiency coefficient

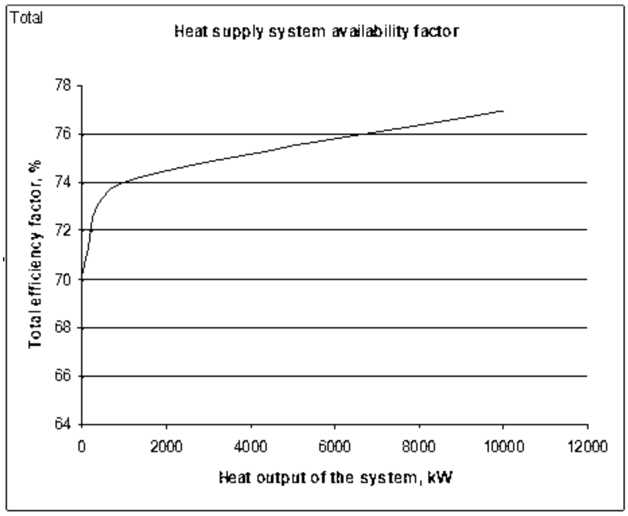

Figure 4. Recommended minimum efficiency values for heat supply systems of different capacities

That is, the minimum permissible overall efficiency coefficient of most urban heating systems should exceed 74%.

The heating system efficiency coefficient can be determined taking into account the efficiency of its individual stages: generation, heat transport and regulated consumption. Therefore:

$$\eta = \eta_g \cdot \eta_l \cdot \eta_r \cdot \eta_u \quad (3)$$

η— overall efficiency coefficient of the heating system, where

η_g— efficiency coefficient of the heat generating installation;

η_l — efficiency coefficient of heat transport and distribution;

η_c — efficiency coefficient of heat consumption regulation for heating devices of various types and performance effectiveness

η_u - efficiency indicator of consumer appliances.

Let us consider the detailed content of the overall efficiency coefficient components, taking into account the extreme conditions' specific features.

The efficiency of a heat generating plant depends, firstly, on its efficiency when burning fuel in a boiler. The main losses that affect efficiency are the exhaust gases temperature, the quality of the burner devices, the load mode and the heat carrier's temperature indicators. The next important indicator is the electricity consumption for the boiler's operation and the heat carrier transport in the heat network per unit of thermal power generated. Under abnormal conditions, when emergency power sources are involved, this component of costs can increase significantly, sometimes several times, which factor must be taken into account in assessing the efficiency of heat generation. The efficiency of heat transport depends mainly on the value of the specific heat losses in the heat network's supply and return mains, the heat network length, as well as on the additional costs for the intermediate heat points operation, if any. In extreme conditions, it is necessary to take into account the possibility of heat loss (heat loss with hot water) in the event of a heat network failure, therefore it is desirable to have backup heat carrier transport routes, the operation of which may also lead to increased costs. To ensure uninterrupted heat supply, of great importance among others is the type of heating main laying (ductless or ducted laying), and another key factor is the system of connections between boiler houses.

CONCLUSIONS

The consumption efficiency coefficient does not directly relate to the efficiency of heat generation and supply to consumers, but it affects the efficiency of the entire heating system. It is important to note quite a series of factors here. These include the perfection of heated buildings thermal insulation, the types and quality of heating devices in the premises, the system of heat supply regulation and distribution to individual consumers in apartment buildings.

It is advisable to place individual heat points in basements, as well as use roof boiler rooms.

In cases of buildings or their glazing partial destruction, a sharp increase in heat losses is possible even while maintaining the integrity of the heating system itself.

As in the case of determining reliability coefficients, the most reliable data on the efficiency of heat generation systems' elements are both the operation data of specific components of the heat supply system in real conditions and generalized statistical analysis data for a significant number of equipment of the same type.

Taking into account the above factors influencing the stability as well as the reliability and efficiency of heat supply systems, with consideration to the extreme conditions, will allow for the implementation of more advanced systems which will be able to provide the necessary conditions for the life of economic activity sectors and the population.

ACKNOWLEDGMENTS

This research work has been supported by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic under grant number KEGA: 008TUKE-4/2025 and VEGA 1/0691/23.

REFERENCES

[Atanasoae 2020] Atanasoae, P. Technical and Economic Assessment of Micro-Cogeneration Systems for Residential Applications. Sustainability, 2020, Vol. 12, No. 3, 1074. DOI: 10.3390/su12031074.

[Cabinet of Ministers of Ukraine 2017] Concept of implementation of state policy in the heat supply field. Approved by the Cabinet of Ministers of Ukraine, Resolution No. 569-p, dated 18. 08. 2017 (in Ukrainian)

[Duhancik 2024] Duhancik, M., Krenicky, T., Coranic, T. Design and Testing of a Measurement Device for High-Speed Bearing Evaluation. Applied Sciences, 2024, Vol. 14, 508. https://doi.org/10.3390/app14020508.

[European Energy Security Strategy 2014] European Energy Security Strategy: Strategy of 28.05.2014 no. 52014DC0330. European Commission. (Accessed: 24.07.2023) Available from: eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52014DC0330.

[Fournier 2023] Fournier S. 5th generation district heating and cooling systems as a renewable solution. ARANER. (Accessed: 24.07.2023). Available from: https://www.araner.com/blog/5th-generation-district-heating-and-cooling-systems.

[Harnicarova 2019] Harnicarova, M., et al. Study of the influence of the structural grain size on the mechanical properties of technical materials. Materialwissenschaft und Werkstofftechnik, 2019, Vol. 50, pp. 635-645. ISSN 0933-5137.

[Klimenko 2018] Klimenko, V. Prospects for application of cogeneration technologies in municipal energy. Thermophysics and Thermal Power Engineering, 2018, Vol. 40, No. 3, pp. 32-37. doi.org/https://doi.org/10.31472/ihe.3.2018.05.

[Klymchuk 2018] Klymchuk, O., Denysova, A., Mazurenko, A., Balasanian, G., Tsurkan, A. Construction of methods to improve operational efficiency of an intermittent heat supply system by determining conditions to employ a standby heating mode. Eastern-European Journal of Enterprise Technologies, 2018, Vol. 6, No. 8, pp. 25-31.

[Klymchuk 2020] Klymchuk, O., et al. Enhancing efficiency of using energy resources in heat supply systems of buildings with variable operation mode. Physics and Engineering, 2020, Vol. 3, pp. 59-68.

[Law of Ukraine 2017] Law of Ukraine: On Heat Supply (2633-IV dated 02.06.2005, as amended). (in Ukrainian)

[Mazurenko 2014a] Mazurenko, A., Denysova, A., Klymchuk, A., Hieu, N.M., Kotov, P. Exergy characteristics of biogas power units. Eastern-European Journal of Enterprise Technologies, 2014, Vol. 1, No. 8, pp. 7-12.

[Mazurenko 2014b] Mazurenko, A., Klimchuk, A., Shramenko, O., Syshova, O. Comparative analysis of decentralized heating systems of residential buildings with the use of electricity. Eastern - European Journal of Enterprise Technologies, 2014, Vol. 5, No. 8, pp. 21-25.

[Nahornyi 2022] Nahornyi, V., et al. Method of Using the Correlation between the Surface Roughness of Metallic Materials and the Sound Generated during the Controlled Machining Process. Materials, 2022, Vol. 15, 823. https://doi.org/10.3390/ma15030823.

[Panda 2014] Panda, A., Prislupcak, M., Pandova, I. Progressive Technology Diagnostics and Factors Affecting Machinability. Applied Mechanics and Materials, 2014, Vol. 616, pp. 183-190. ISSN 1660-9336.

[Panda 2020] Panda, A., et al. A novel method for online monitoring of surface quality and predicting tool wear conditions in machining of materials. International Journal of Advanced Manufacturing Technology, 2022, Vol. 123, No. 9-10, pp. 3599-3612.

[Panda 2021] Panda, A., et al. Increasing of wear resistance of linear block-polyurethanes by thermal processing

methods. MM Science Journal, 2021, Vol. October, pp. 4731-4735.
[Panda 2022] Panda, A., et al. Ecotoxicity Study of New Composite Materials Based on Epoxy Matrix DER-331 Filled with Biocides Used for Industrial Applications. Polymers, 2022, Vol. 14, No. 16, Article no. 3275. ISSN 2073-4360.
[Pandova 2020] Pandova, I., et al. A study of using natural sorbent to reduce iron cations from aqueous solutions. International Journal of Environmental Research and Public Health, 2020, Vol. 17, No. 10, Art. no. 3686. ISSN 1661-7827.
[Radosavljevic 2018] Radosavljevic, M. Application of small and micro cogeneration units. Vojnotehnicki glasnik, 2018, Vol. 66, Issue 2, pp. 431-445. DOI: 10.5937/vojtehg66-7309.
[Sagova 2025] Sagova, Z., et al. Improving the Accuracy of Air Temperature Monitoring for Automated Tasks in Agriculture Using Affordable Meteorological Equipment. Acta Technologica Agriculturae, 2025, Vol. 28, No. 3, pp. 176-182. https://doi.org/10.2478/ata-2025-0022.
[Sukhodub 2018] Sukhodub, L., Panda, A., Dyadyura, K., Pandova, I., Krenicky, T. The design criteria for biodegradable magnesium alloy implants. MM Science J., 2018, Vol. December, pp. 2673-2679.
[Sukhodub 2019] Sukhodub, L., Panda, A., Sukhodub, L., Kumeda, M., Baron, P. Hydroxyapatite and zinc oxide based two-layer coating, deposited on Ti6Al4V substrate. MM Science Journal, 2019, Vol. December, pp. 3494-3499.

CONTACTS:

Anton Panda, Prof. Ing. PhD.
Faculty of Manufacturing Technologies with a seat in Presov
Technical University of Kosice
Sturova 31, 080 001 Presov, Slovakia

Faculty of Technology
Institute of Technology and Business in Ceske Budejovice
Okružni 10, Ceske Budejovice, Czech Republic
e-mail: anton.panda@tuke.sk

Anton Mazurenko; Oleksandr Klymchuk; Ganna Pozdniakova; Anatoliy Pustovit
Odesa Polytechnic National University
Department of of Energy
Shevchenka Ave 1, 65044 Odesa, Ukraine

Jan Valicek; Marta Harnicarova
Slovak University of Agriculture in Nitra
Faculty of Engineering
Institute of Design and Engineering Technologies
Tr. A. Hlinku 2, Nitra, 949 76, Slovakia

Faculty of Technology
Institute of Technology and Business in Ceske Budejovice
Okružni 10, Ceske Budejovice, Czech Republic*