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The first issue of the journal "Podzemni radovi" (Underground Mining Engineering) was published back in 1982. Its founders were: Business Association Rudis - Trbovlje and the Faculty of Mining and Geology Belgrade. After publishing only four issues, however, the publication of the journal ceased in the same year.

Ten years later, in 1992, on the initiative of the Chair for the Construction of Underground Roadways, the Faculty of mining and Geology as the publisher, has launched journal "Podzemni radovi". The initial concept of the journal was, primarily, to enable that experts in the field of underground works and disciplines directly connected with those activities get information and present their experiences and suggestions for solution of various problems in this scientific field.

Development of science and technique requires even larger multi-disciplinarity of underground works, but also of the entire mining as industrial sector as well. This has also determined the change in editorial policy of the journal. Today, papers in all fields of mining are published in the "Underground Mining Engineering", fields that are not so strictly in connection with underground works, such as: surface mining, mine surveying, mineral processing, mining machinery, environmental protection and safety at work, oil and gas engineering and many others.

Extended themes covered by this journal have resulted in higher quality of published papers, which have considerably added to the mining theory and practice in Serbia, and which were very useful reading material for technical and scientific community.

A wish of editors is to extend themes being published in the "Underground Mining Engineering" even more and to include papers in the field of geology and other geo-sciences, but also in the field of other scientific and technical disciplines having direct or indirect application in mining.

The journal "Underground Mining Engineering" is published twice a year, in English language. Papers are subject to review.

This information represents the invitation for cooperation to all of those who have the need to publish their scientific, technical or research results in the field of mining, but also in the field of geology and other related scientific and technical disciplines having their application in mining.

Editors

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Original scientific paper

SELECTION OF BUSINESS MODELS IN UNSTABLE CONDITIONS IN MINING COMPANIES

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Abstract: This paper aims to rank business models for successfully overcoming socio-economic instability through criteria using an appropriate multicriteria decision-making method (MCDM). In this paper, the AHP method was used to calculate the difficulty criteria. The literature review identified and analyzed six business models: digital business models where companies will be found, competitive advantage models, global, deglobal, market models based on new products and services and customer-built business models. The findings of this research improve the understanding of several business models on the basis of which the management of mining companies can successfully overcome the socio - economically unstable situation.

Keywords: Business Models, Unstable Situation, Mining Companies

1 INTRODUCTION

The Covid-19 pandemic and the war in Ukraine created an unstable socio-economic situation on a global level. The unstable situation has affected all branches of the economy in the world. Globalization has created an interconnectedness between all companies. The Covid 19 pandemic globally has led to a decline in and demand for many products and services, many jobs have slowed or stalled including the mining industry (Galas et al., 2021).

Unstable socio - economic situation has led to an increase in prices of products and services. The prices of precious metals have risen sharply on a global scale.

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In such a socio - economically unstable situation, it is important to identify possible business models that would bring managers safe and sustainable business in mining companies.

The AHP (Analytical Hierarchical Process) method was used to select possible business models in mining companies. The AHP method belongs to the multicriteria decision making (MCDM) methods. The calculation of the AHP method is flexible, it enables the solution of complex problems with several criteria and alternatives. The AHP method analyzes the criteria in terms of the importance of one criterion in relation to others. A further procedure is to compare each criterion with each alternative in relation to the given goal.

By selecting appropriate business models, this paper contributes to increased security during a socio-economically unstable situation in performing mining business activities.

2 LITERATURE REVIEW

A review of the literature shows that the identification of business models in a socially - economically unstable situation is becoming increasingly important. The term "business model" appeared in the 40 years twenty century in works on economics. But only 90 years ago, they became popular in management and economics in various fields. Business models are the forms or ways in which employees think about which methods they can use to best implement business goals while generating revenue.

Mining companies in Serbia have started cooperation with multinational companies in the world. Multinational corporations operate in accordance with the law and environmental standards of Serbia. But with the construction of certain mines in Serbia during the socio-economically unstable situation we are currently in, there is a danger of damage to the environment. Although the esteemed literature on mine management is available to managers and mining experts, the desire is to increase the safety situation in the mines.

In unstable conditions, modern business is changing globally, where there are big changes in all business segments. The form of modern business at the global level is changing in the procurement of goods and services (Bals and Turkulainen 2021); in green practice of hospitality conditions Piya et al. (2022); in circular economy (Husain et al. 2021) etc. Current changes in the global environment affect all significant factors in the postal sector (Milutinović and Popović, 2020) and other segments. Authors Husain et al. (2021) analyzed business models for the implementation of circular economy by MCDM methods, Fuzzy TOPSIS approach. Because the transition of a linear economy to a circular one requires the construction of new business models that exceed the limitations of the linear model of the economy. The analysis of the practice of green management in the hotel industry was performed using the integrated Fuzzy AHP-TOPSIS method.

Doing business in the global world is changing the way we do business due to the development of new technologies, digitalization, pandemics such as Covid-19 and wars. Digitization is increasingly becoming a priority in business circumstances. In global business, society as a whole is undergoing radical changes due to the development of digital technologies.

In mining as well as in energy, digitalization is applied, digital procedures e - mining. E-mining brings a new way of doing business: e-invoicing (electronic invoicing), e-billing, e-bookkeeping, e-postman-electronic exchange and signing of contracts and documents and much more. All the above options facilitate the implementation of the business strategy of mining in a socially - economically unstable situation.

The current socio-economic instability was produced by the Covid-19 pandemic and the war in Ukraine. These current changes in the global environment greatly affect significant factors in the mining sector - the creators of the e-mining strategy. The implementation of digital technology in the mining sector brings increased competition, customer satisfaction, profits and customer confidence in products and services (Miletić et al., 2021). While the analysis of the impact and consequences of COVID-19 on the use of non-renewable natural resources shows a decline in business volume and profitability of companies, excessive growth in gold prices and high energy uncertainty (Bogdanović and Miletić, 2021).

Unstable socio - economic situation sets new needs for users (customers), major changes in products and services, which implies the development of new business mining models.

In this paper, first of all, the criteria with which we evaluate alternatives, business models are given. The criteria were identified through the literature based on Osterwalder this business model. Alternatives were provided by sending a questionnaire to managers of mining companies using digital technology. Using the AHP method, the weight coefficients of the criteria were determined and the sustainable business model during socio - economic instability was assessed.

3 WORK METHODOLOGY

The methodology of the paper first defines the goal of the paper by the author in order to obtain relevant results. The aim of this paper is to choose business models in socio - economically unstable conditions in mining companies.

Hypothesis I: Built business models in socio-economic instability in mining companies can be sustainable through modeling.

Hypothesis II: Some of the built business models in socio-economic instability in mining companies cannot be sustainable.

One of the most famous in the world is the Osterwalder business model. There are 9 segments in the Osterwalder model that we use to identify the criteria. Dr. Alexander (Alex) Osterwalder is one of the world's most influential experts in business model strategy and innovation. As a lead author, entrepreneur Osterwalder gave an overview of how core companies operate and how new ventures begin.

Figure 1 shows the multidimensional hierarchical structures of the AHP method. The goal is to choose business models in mining companies.

The methodology begins with the identification of the criteria that define the business model.

Eligibility criteria:

1. Market analysis, consumer segments (C1),
2. Customer, needs satisfaction assessments (C2),
3. Method of delivery of goods to customers, sales channels (C3),
4. Customer relationship, customer attraction (C4),
5. Key resources, which resources the company has (C5),
6. Key activities to be performed (C6),
7. Important market entry partners (C7) i
8. Revenue structure (C8),
9. Finally, costs, what are the costs (whether this model is sustainable or not) (C9).

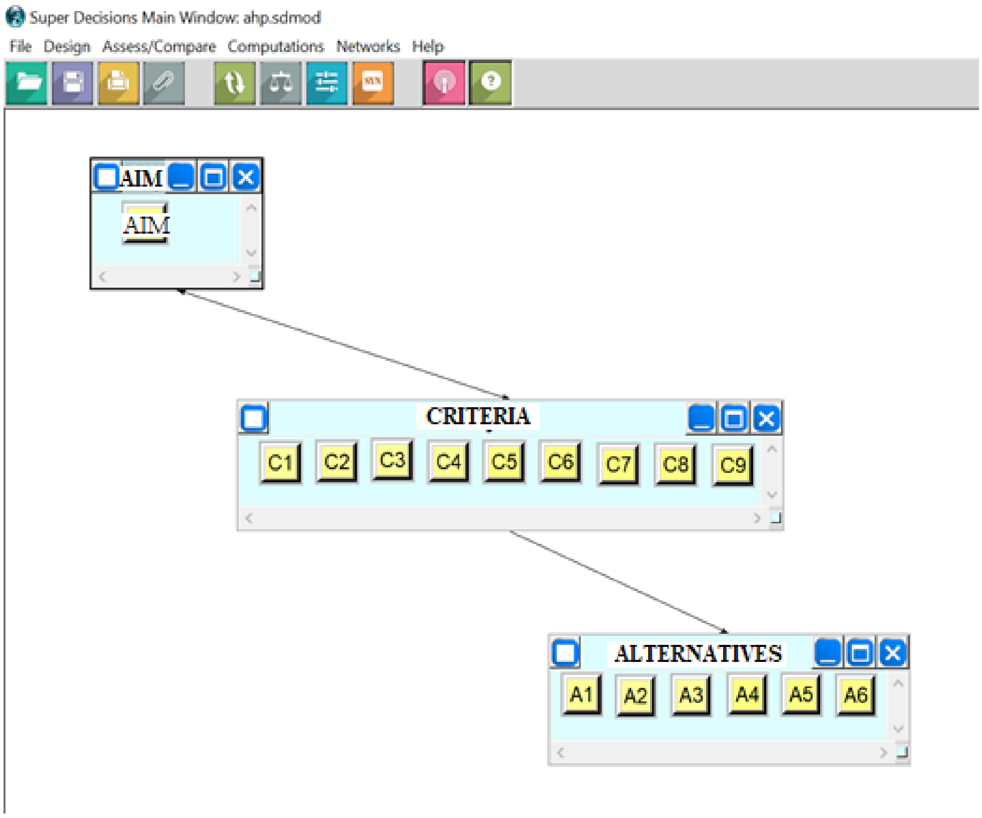

Figure 1 Multidimensional hierarchical structure of the AHP method

The weighting coefficients of the criteria and alternatives are calculated using the AHP method using the Super Decisions software based on the Sati scale Table 1. We first evaluate the criteria with each other, defining the weight coefficients of the criteria Table 2. A further course of research is to compare the alternative with each criterion individually in relation to the given goal – Tables 3-11.

The standard AHP uses a degree of consistency (CR), its value is less than 0.1. During the analysis, a check is performed and if the degree of consistency has a higher value, the values entered in the comparison matrix are recalculated. In our case, the degree of consistency has a value of 0.05700, which means CR consistent. The results of the ranked criteria using Super Decisions software are shown in Figure 2.

Table 1 Satie's scale for comparing two elements

$$S=\left\{\frac{1}{9},\frac{1}{8},\frac{1}{7},\frac{1}{6},\frac{1}{5},\frac{1}{4},\frac{1}{3},\frac{1}{2},1,2,3,4,5,6,7,8,9\right\}$$

Value ajk	Analysis of results
1	The elements j and k are equally important
3	The element j is somewhat more important than k
5	Element j is more important than k
7	The element j is much more important than k
9	The element j is absolutely more important than k
2,4,6,8	Intermediate values between two elements

Table 2 Defining the weighting coefficients of the criteria

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	1	1/2	1/2	1	1/3	2	1/2	1/2	1
C2		1	2	1	1/2	1/2	1/2	1/2	2
C3			1	1/2	1/3	1	1/2	1/3	1/2
C4				1	1/3	1	1/2	1/3	1
C5					1	3	3	2	2
C6						1	1	1/2	1/2
C7							1	1/2	1/2
C8								1	1
C9									1

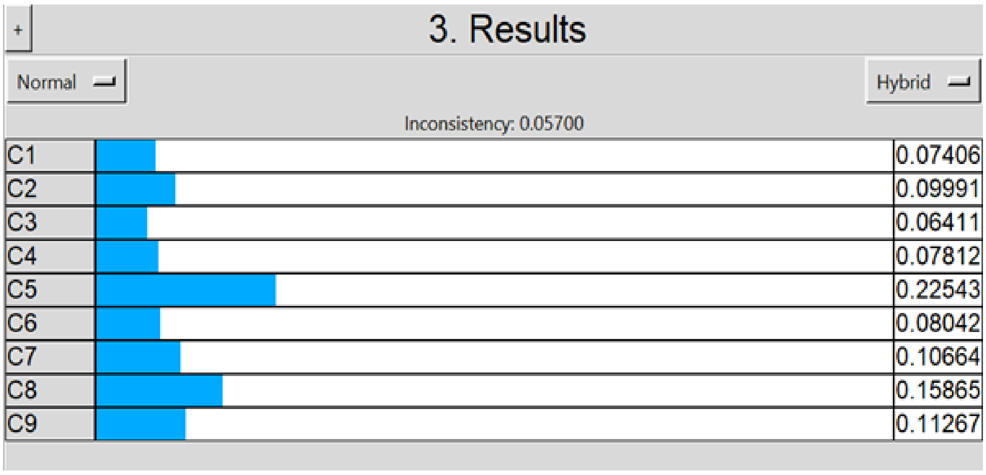

Figure 2 Results of the ranking of criteria

Further research is the collection of data on possible business models in unstable business conditions. Data collection was done by sending a questionnaire by digitalization to managers of selected companies. Digital technology in unstable business situations serves as an aid to achieving a given goal.

Possible business models are defined by the authors together with the managers of the mining company. We evaluate defined business models using the AHP method together with managers, group decision-making with the help of Super Decisions software.

Defined business models:

1. Alternative A1 – digital business models where companies will be found,
2. Alternative A2 – competitive advantage models,
3. Alternative A3 – global,
4. Alternative A4 – deglobal,
5. Alternative A5 – market models based on new products and services and
6. Alternative A6 – business models built to customer satisfaction.

Defined business models by authors and managers are evaluated by criteria (Tables 3-11). Some modeling can always be performed until an accurate hypothesis is obtained.

The goal of authors and managers is to model business models during socio-economic instability as a way of survival and development of the company.

Table 3 Comparison of alternatives in relation to criteria C_1 (Market analysis, consumer segments)

Alternative	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**
A_1	1	1	1/2	2	1/2	1/3
A_2		1	2	3	1	1/2
A_3			1	3	1/3	1/2
A_4				1	1/2	1/3
A_5					1	1
A_6						1

Table 4 Comparison of alternatives in relation to criteria C_2 (Customer needs satisfaction assessments)

Alternative	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**
A_1	1	1/2	1	2	1/3	1/3
A_2		1	1	2	1/2	1/2
A_3			1	1/2	1/3	1/2
A_4				1	1/2	1/2
A_5					1	1
A_6						1

Table 5 Comparison of alternatives in relation to criteria C_3 (Method of delivery of goods to customers, sales channels)

Alternative	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**
A_1	1	2	1	2	1/2	1/2
A_2		1	1/2	2	1	1/2
A_3			1	1/2	1/2	2
A_4				1	1/2	1/2
A_5					1	1
A_6						1

Table 6 Comparison of alternatives in relation to criteria C_4 (Customer relationship, customer attraction)

Alternative	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**
A_1	1	1/2	1	2	1/3	1/3
A_2		1	2	2	1	1
A_3			1	1/2	1/2	1/2
A_4				1	1/3	1/3
A_5					1	1
A_6						1

Table 7 Comparison of alternatives in relation to criteria C_5 (Key resources, which resources the company has)

Alternative	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**
A_1	1	1/2	1	2	1	1
A_2		1	1	3	1/2	1/2
A_3			1	3	1	1
A_4				1	1/2	1/2
A_5					1	1
A_6						1

Table 8 Comparison of alternatives in relation to criteria C_6 (Key activities to be performed)

Alternative	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**
A_1	1	1/2	1	2	1	1
A_2		1	2	2	1/2	1/2
A_3			1	2	1	1
A_4				1	1/2	1/2
A_5					1	1/2
A_6						1

Table 9 Comparison of alternatives in relation to criteria C_7 (Important market entry partners)

Alternative	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**
A_1	1	1/2	1/3	3	1/2	1
A_2		1	1	2	1/2	2
A_3			1	3	2	2
A_4				1	1/3	1/3
A_5					1	1/2
A_6						1

Table 10 Comparison of alternatives in relation to criteria C_8 (Revenue structure)

Alternative	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**
A_1	1	2	1	3	1/2	1/2
A_2		1	1	2	1/2	1
A_3			1	2	1	1
A_4				1	1/2	1/2
A_5					1	1/2
A_6						1

Table 11 Comparison of alternatives in relation to criteria C_9 (Costs, what are the costs (whether this model is sustainable or not)

Alternative	**A_1**	**A_2**	**A_3**	**A_4**	**A_5**	**A_6**
A_1	1	3	2	3	1	1/2
A_2		1	1/2	1/3	1	1
A_3			1	2	1/2	1/3
A_4				1	1/3	1/3
A_5					1	1
A_6						1

Figure 3 shows the ranked alternatives with weighting coefficients.

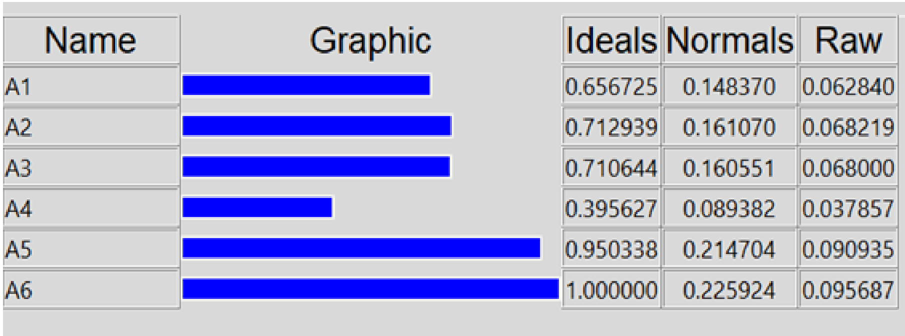

Figure 3 Results of the ranking of the alternatives

4 ANALYSIS OF RESULTS

Criteria analysis: AHP calculation showed that criteria C5 – key resources, which resources the company has been the most important and because their weighting factor has the highest value of 0.22543. This means that criteria C5 has the greatest impact on determining business models because it ranks first. In an unstable socio-economic situation, it is very important that company managers have key resources in choosing business models, namely human, natural, and material resources.

Criteria C8 – the revenue structure ranks second. The weighting factor of criteria C8 is 0.15865. Revenue structure is also important when choosing business models because if there is no revenue there is no survival of the company.

Criteria C9 (costs, what are the costs, whether this model is sustainable or not), C7 (important partners for market entry) and C2 (customer satisfaction assessments) are in third place because their weighting coefficients have approximate values. The values of the coefficient of criteria C9 is 0.12267, of criteria C7 is 0.10664 and of criteria C2 is 0.09991. When choosing business models, costs must not exceed the allowable ones, when costs increase, revenues decrease. For the companies, the business partners they work with are important, due to the conquest of the market and the assessment of the customer. Assessment and customer satisfaction with products and services is performed quarterly within the quality management system (QMS) by digital surveys.

By calculation, we get that the following criteria take the fourth place:

- C6 – Key activities to be performed with weighting factor 0,08042,
- C4 – Customer relationship, customer attraction with weighting factor 0,07812,
- C1 – Market analysis, consumer segments with weighting factor 0, 07406, i
- C3 – Method of delivery of goods to customers, sales channels with weighting factor 0,06411.

Company managers choose key activities that will bring profit to the company, carefully analyze the market, then attract customers in various ways and make decisions about the best product delivery.

Alternative analysis:

From Figure 3 we come to the conclusion that alternative A6 – business models built to customer satisfaction is the most optimal business model because its weighting factor has the highest value of 0.225924.

In second place is the alternative A5 – market models based on new products and services with a weighting factor of 0.214704.

The third place is occupied by A2 – models of competitive advantage, whose value of the weight coefficient is 0.161070.

In fourth place is the global model (A3) with a weighting factor of 0.160551.

The fifth place is taken by alternative A1 – digital business models where companies will be found, whose weight coefficient is 0.148370.

The last place is occupied by A4 – deglobal, whose value is 0.089382.

Business models built to customer satisfaction and market models based on new products and services in socio-economic instability have the greatest success of survival with mining companies. While the results show that the proposed deglobal business model is not sustainable for mining companies. Business models of competitive advantage, global and digital, can always become sustainable through modeling in unstable conditions.

Conclusion: Given Hypothesis I: Built business models in socio - economic instability in mining companies can be sustainable through modeling, namely: business models of competitive advantage, global and digital.

Hypothesis II: Some of the built business models in socio-economic instability in mining companies cannot be sustainable (business deglobal models).

5 CONCLUSION

The form of modern business at the global level is constantly changing, especially during socio-economic instability. The unstable business situation, COVID-19 and the war in Ukraine encouraged the authors to propose and rank business models with mining companies together with the managers of mining companies.

The aim of this paper is to evaluate the proposed business models for successfully overcoming socio-economic instability. Based on the Osterwalder of this business model, criteria were identified. Dr. Alexander (Alex) Osterwalder is one of the world's most influential experts in business model strategy and innovation. The AHP method was used to calculate the weight of the criteria and rank the alternatives.

By defining the weight coefficients of the criteria, we get:

- Criteria C5 takes the first place, key resources have the greatest influence on the choice of business models because their weight coefficient has the highest value of 0.22543;
- The second place is occupied by criteria C8 – income structure with a weighting factor of 0.15865;
- Third place is occupied by criteria C9 – costs with a weighting factor of 0.12267, criteria C7, important partners for entering the market with a weighting factor of 0.10664 and criteria C2 – the customer's estimate with a weighting factor is 0.09991;
- The fourth place is occupied by the following criteria:
    - C6 – Key activities to be performed with weighting factor 0,08042,
    - C4 – Customer relationship, customer attraction with weighting factor 0,07812,
    - C1 – Market analysis, consumer segments with weighting factor 0, 07406,
    - C3 – Method of delivery of goods to customers, sales channels with weighting factor 0,06411.

Further research showed that the selected business models A6 – built to customer satisfaction (0.225924) and A5 – market models based on new products and services

(0.214704) have the greatest success of the survival of the mining company in unstable conditions.

Business models of competitive advantage A2 (0.161070), global A3 (0.160551) and digital A1 (0.148370) after modeling and development over time can become sustainable. Business model A4, deglobal, with a value of 0.089382, is not sustainable in unstable conditions.

Authors of future research can address the question of how selected business models affect the management of mining companies.

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Original scientific paper

TRANSFORMATIONS OF MECHANOCHEMICAL ACTIVATED Na_2CO_3

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Received: September 28, 2022 **Accepted:** November 03, 2022

Abstract: During mechanical activation, energy of treated material is increase to a higher level. This can lead to chemical transformation of the activated material. This is the point where we can talk about mechanochemical transformations that have occurred as a result of mechanical activation. The subject of this paper is to monitor mass changes of material after different degrees of activation. One of the substances which is often used in the processes of mechanochemical synthesis is sodium carbonate. The mass changes occurring during the treatment were detected and measured by various methods, depending on the processing environment. The mass increase was attributed to chemisorption of moisture and carbon-dioxide present in air, as a consequence of the sodium carbonate activation. The methods we used were calcimetric chemical analysis. According to obtained results, it was found that activated sodium carbonate is mass-transformed into sodium bicarbonate, whereby these changes are functionally dependent on activation time and the processing atmosphere.

Keywords: Mechanical activation, sodium carbonate, mechanochemical transformation

1 INTRODUCTION

Mechanical activation (MA) of materials is widely used as a process of bringing additional energy to a system to begin a controlled reaction. This allows the system to be moved across the "energy barrier" that is in the reaction's path. MA is among the most interesting fields of investigation. It is relating the activation of solid materials, also more often used in practice throughout the world. The results achieved by numerous researchers show that mechanical activation results in accumulation of mechanical energy in processed material, accompanied by various changes and improved physico-chemical characteristics of material. These changes contribute to faster, more simple and qualitatively better development of certain processes usually performed by conventional chemical methods. It also causing significant savings in time and cost of preparation

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process. Moreover, certain chemical processes proceeding in one way may change their course during or after the mechanical treatment, thus providing quite different products which could not be obtained in other ways.

Various materials nowadays are prepared by MA, such as cordierite-based, alumina-based, titanate-based, spinels and many others. Sodium carbonate is a substance that responds extremely well to mechanochemical treatment, with its chemical activity significantly increasing due to the weakening of the chemical bonds in the crystal lattice. Due to these characteristics, there is a possibility of extensive use of sodium carbonate in the mechanochemical reactions of synthesis of various substituents, which would replace the classical chemical processes in extreme working conditions.

Mechanochemistry is a modern scientific problem, and it deals with the physico-chemical changes of substances due to the action of mechanical energy. Studying the reactions in the solid phase after mechanical activation, we can get the information of certain properties of material acquired during mechanical treatment.

The basics of mechanochemical treatment of materials were laid by V. V. Boldyrev, B. V. Deryagin, P. A. Rebinder, A. N. Frumkin, E. D. Shchukin, N. A. Kratove, D. V. Kusnecov, and others (Dunkić et al., 1996). There are different areas of interest in studying the mechanochemical action on materials. Considering the influence of the action of several types of devices for transferring mechanical energy to materials and the development of new ones are presented as well (Dallacqua et al., 1998; Belyaev et al., 1998; Boldyrev et al., 1998). Different conditions (temperature, atmosphere, intensity, and mode of transmission of mechanical energy, etc.) as well as the setting of kinetics and mechanism of mechanochemical processes were also presented (HCS Chemistry; Obradović et al., 2019). As a result of mechanochemical action in materials, defects occur, crystal structure destruction and amorphous phase formation. Monitoring of these effects are given in papers (Filipović et al., 2018; Živojinović et al., 2019). Different methods and possibilities of new testing methods for characterization of materials after mechanical activation have been studied as a function of different parameters (relaxation time, temperature, atmosphere in which the sample is located, possible reactions in multicomponent systems) (Lazarević et al., 2017; Obradović et al., 2016).

2 EXPERIMENTAL PROCEDURE

During this research, the sodium carbonate system, p.a.MERCK index 11.8541, was activated by a mechanochemical process. The bond energy values represented by sodium carbonate are Na–O (364 kJ/mol), C–O (1076.4 kJ/mol), C=O (532.2 kJ/mol).

The decomposition temperature of sodium carbonate is 851 °C. Sodium carbonate has a monoclinic crystal lattice (a = 8.907; b = 5.239; c = 6.043), with a specific mass of 2500 kg/m^3. The chemical composition of sodium carbonate according to the MERCK index 11.8541.

A chemical analysis was performed on a representative sample. Sodium carbonate was mechanochemically activated in a high energy mill with torsion springs and “KHD HUMBOLDT WEDAGAG” ring elements. The volume of the mill's working vessel was 2 dm^2 and the mass of material that can be activated under optimal conditions is 200 g. Engine power was 0.8 kW. The device operates discontinuously in an atmosphere of air. Intensely vibrating movement of the mill work piece with massive rings causes the vessel to warm up to a temperature of 80 ^oC.

A sample of Na_2CO_3, weighing 50.0 g, was activated by a mechanical procedure for 1 to 28 min. Activated samples were deposited under different conditions at room temperature, in a carbon dioxide atmosphere and in a vacuum. The sample residence time was from 1 to 85 days. The samples were exposed to a room temperature. As a function of the activation time in the mechanical-chemical reactor, the residence time of the sample after activation and the atmosphere in which the sample was located, changes were monitored on activated sodium carbonate using different methods.

The effects of MA of sodium carbonate were monitored by measuring the change in mass of the activated sample, calcimetric analysis. The following instrumental technique was used. A standard laboratory calculator was used to quantify the content of sodium carbonate as well as to monitor the process of carbon dioxide chemisorption from the atmosphere in which the sample was located, over the carbonate content of the test sample.

3 RESULTS AND DISCUSSION

3.1 Change in sample mass as a function of activation time

A sample of 50.0 g anhydrous Na_2CO_3 was activated by a mechanochemical process in a vibrating mill for 1, 4 and 7 min. Both inactive and activated samples were deposited at room temperature under carbon dioxide, vacuum and room conditions for 64 days. Mass samples changes was monitored as a function of activation time, and also the time that samples were exposed to the given conditions. The measurement results are shown in Figure 1.

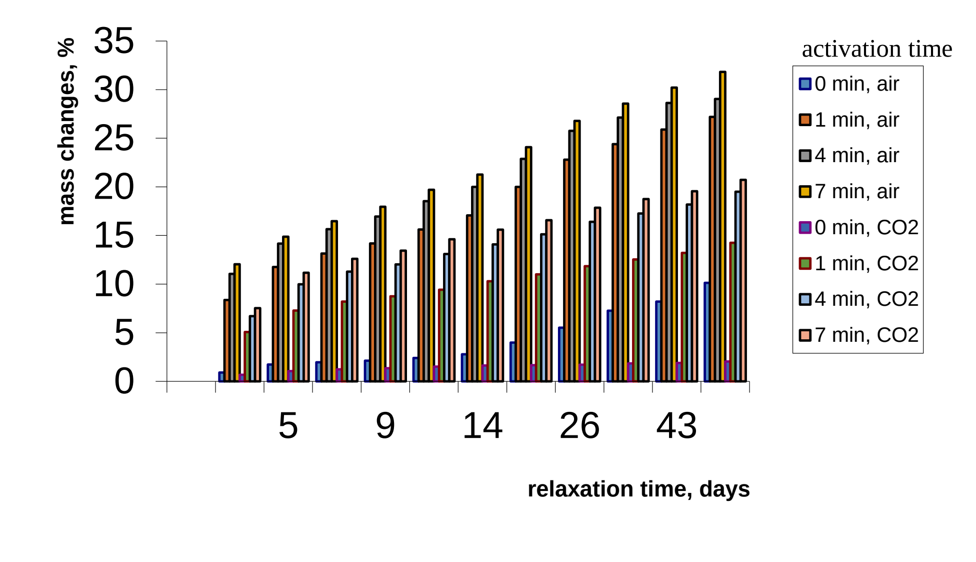

Figure 1 Mass increase of inactivated and activated Na_2CO_3 samples under room conditions and CO_2 atmosphere

The samples activated for 1, 4 and 7 min, as well as the inactivated sample of sodium carbonate that were in vacuum, had no mass changes for 64 days. Samples that were stored in carbon dioxide at room temperature as a function of relaxation time, changed as follows: the non-activated sample of sodium carbonate increased by 2.039 % over a 64-day period. The 1 min activated sample mass increased 14.25 %, the 4 min activated sample weight increased 19.50 %, and the 7 min activated sample mass increased 20.73 %. The increase in sample mass is due to the absorption of carbon dioxide and the moisture present throughout the sample volume. Inactivated sodium carbonate mass change showed that mass increased 10.13 % under room atmosphere and temperature conditions for 64 days. The 1 min activated sample mass increased 27.20 %, the 4 min activated sample 29.05 %, and the 7 min activated sample increased 31.83 %. The increase in the mass of these samples was due to the absorption of moisture and carbon dioxide from the air. Based on these results, it can be concluded that the mass of the samples increases as a function of the time of activation of the sodium carbonate in the vibrating mill, that is, the samples increase the absorption capacity with the extension of the activation time.

3.2 Changing mass of activated Na_2CO_3 in CO_2 atmosphere and increased humidity as a function of activation time

As the activated sodium carbonate samples show a tendency of increased absorption power, the continuation of the experiment of monitoring the changes in the relaxation of the activated samples was carried out in a closed vessel, at room temperature, in a CO_2 atmosphere, in which, beside the samples, there was a water tank. The carbon dioxide pressure was 1 bar and the humidity was about 95 %. The Na_2CO_3 samples were activated 1, 3, 5, 7, 14, 21, and 28 min. The relaxation time was 24 days. Changes in sample mass as a function of activation time and relaxation time were monitored. The measured samples also contained a sample of inactivated sodium carbonate. The results are shown in Figure 2.

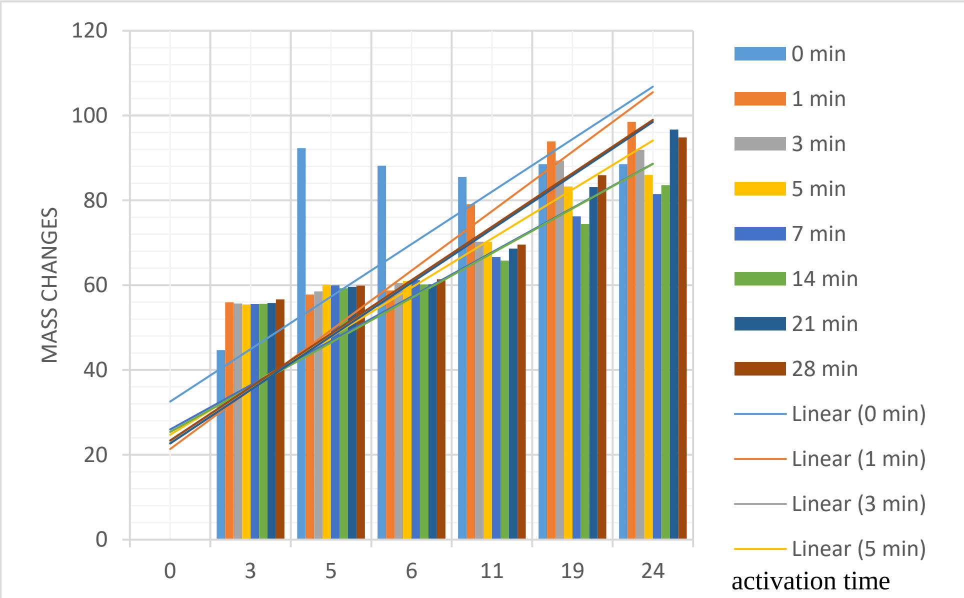

Figure 2 Mass changes of inactive and activated Na_2CO_3 in CO_2 atmosphere at 95 % humidity, as a function of the relaxation time

Figure 2. shows that the inactivated sample under these conditions rapidly increases mass (up to almost 90 %) during the first 5 days of the relaxation time due to the absorption of moisture from the atmosphere by water vapor. After this time, the mass of the inactive sample remained almost unchanged. This behavior of the inactivated sample can be explained by the fact that the entire volume of Na_2CO_3 has been bound by the presence of moisture from the atmosphere in the form of crystalline water. Based on the results obtained, it can be concluded that 5.3 moles of water per mole of sodium carbonate have been absorbed by the fifth day of monitoring the change in mass of the unactive sample. This change in the sample was due to the hygroscopicity of the anhydrous sodium carbonate.

All samples that were subjected to MA in the first 3 days of the mass relaxation time increased almost identically up to 60 %. After the third day, one period of stagnation occurs until the sixth day, after which the mass of samples again tends to increase, so that by the 24th day, as a function of the time of activation, it increased 80–90 %. It can be noticed a significant difference in the behavior of inactivated and activated Na_2CO_3. Unlike the simple absorption that occurs with inactivated sodium carbonate, this behavior of the activated samples can be explained by the assumption that during the mechanical activation there was a weakening and breaking of the chemical bonds in the sample, and thus an increase in the chemical activity of Na_2CO_3. Since such a sample was, after activation, contained in an atmosphere of CO_2 and moisture present, it may be that during the first three days of relaxation, their chemisorption by sample volume and $NaHCO_3$ formation occurred. After three days of stagnation, the sample mass begins to grow again due to the subsequent absorption of moisture by the resulting bicarbonate. The reaction by which the process of chemisorption of carbon dioxide and moisture probably occurs, that is, the possible conversion of sodium carbonate to sodium bicarbonate is as follows:

$$2Na_2CO_{3(s)} + H_2O_{(g)} + CO_{2(g)} \rightarrow 2NaHCO_{3(s)}$$

Due to the behavior of the samples during the relaxation time, further analyses were necessary to confirm the assumption that the activation of sodium carbonate increases chemical activity and, consequently, due to the presence of CO_2 and moisture in the atmosphere, conversion to $NaHCO_3$ occurs.

4 CONCLUSION

The results of the study show that by holding the activated Na2CO3 sample at room conditions, the sample mass grows due to the absorption of moisture and carbon dioxide from the air. The mass of the samples increased as a function of the grinding time of sodium carbonate at the same relaxation time. By the presence of activated samples in the atmosphere of carbon dioxide, the masses of activated samples also increase as a function of the time of activation, while the mass changes are smaller than the samples that were stored at room conditions.

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Review paper

COAL CLEANING BEFORE COMBUSTION – PRACTICE AND EXPERIENCE IN SERBIA

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Abstract: The paper gives review of international and domestice experience in Serbia in the field of coal cleaning prior to combustion in thermal power plants. Also, the paper highlighted the problem of combustion low rank lignite from open pit mine in thermal power plants and considering this problem from the aspect of mineral processing. The results of laboratory tests aimed to establish the possibility of cleaning of lignite from Tamnava Zapadno polje, showed the beneficial upgrading of the 70% of run-of-mine coal with simple screening. It has been confirmed that by simple process of coal cleaning can be removed about 30% of tailings, which mostly consist of mineral impurities. The final obtained products have satisfactory quality (lower contents of ash and higher calorific values).

Keywords: Lignite, Coal cleaning, Coal quality, Thermal power plants

1 INTRODUCTION

Coal plays a vital role in electricity generation worldwide. Coal-fired power plants currently fuel 37% of global electricity and data from IEA show that coal will still generate 22% of the world's electricity in 2040, retaining coal's position as the single largest source of electricity worldwide (Word Coal Association, 2022). Public Enterprise Electric Power Industry of Serbia (EPS) is the most reliable power system support of Serbia. The mean annual generation between 2010 and 2020 was 34.896 GWh of electricity. The capacities for generation of electricity operated by EPS total to 7.855 MW. EPS thermal power plants generate about 70% of electricity in Serbia, while about 30% is generated in 16 hydropower plants (EPS, 2022a).

Coal produced in mining basin Kolubara in Serbia provides about 53% of electricity in EPS, and coal from Kostolac open pit provides 17% of electricity production. Total coal production of coal in EPS in 2020 amounted to 39.1 million tons. Mining basin Kolubara produces an average of 29 to 30 million tons of coal. Kostolac coal basin produces an average of about 9 million tons of coal (EPS, 2022b). From 9 underground mines that

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operate within JP PEU Resavica is produced about 500.000 tons of high-quality coal per year. However, this coal participates with about 1.3% in total electricity production (JP PEU Resavica, 2022).

Based on all the above mentioned, it is obviously that coal from surface mining will be the main source of energy in Serbia in the future.

All coals contain noncombustible mineral matter which residue after coal has been burned is called ash. From the standpoint of coal cleaning, impurities occurring in coal may be classified as ash-forming and the sulfur-containing impurities, which both can be subdivided into inherent impurities and extraneous impurities. The inherent impurities are inseparably combined with the coal, while the extraneous impurities are segregated. Ash-forming material organically combined with the coal is considered inherent mineral matter. Extraneous mineral matter is ash-forming material from detritial matter and consists usually of slate, shale, sandstone, limestone or clay or other extraneous mineral matter from the roof and floor of the mine. All extraneous matter can be removed, i.e. separated physically with various method (Hower and Parekh, 1991).

The goal of coal preparation is to maximize the value of the coal material by separating the coal from the waste impurities to shipment to the end consumer (Noble and Luttrell, 2015).

The processes of coal preparation include coarse and intermediate coal cleaning (in dense medium vessels and dense medium cyclones) and fine and ultrafine coal cleaning (in spirals, water-only-cyclones, teeter-bed separators, conventional and column flotation cells). For coarse and intermediate size classes, crushing and screening is efficient methods for size reduction and classification. Grizzlies, inclined vibratory screens, high frequency screens and banana screens are often utilized for screening, while hammer mills, sizers and jaw crushers are the most popular machines for crushing (Bethell and Luttrell, 2004; Noble and Luttrell, 2015; Waymel and Hatt, 1988).

Thermal power plants have the capacities of boilers designed for a certain quality of coals. It is generally known, and confirmed through the paper of other authors, that combustion of coal with higher calorific values, lower ash and moisture contents, enables high boiler efficiency (Bureska, 2017; Harikrishnan et al., 2016; Saxena, 2013; Waymel and Hatt, 1988).

In the structure on pathway of the coal heat energy flow from deposit to the delivered electricity, only 24% of available energy is delivered to the users, while 15% of available energy went to exploitation losses, 10% to coal cleaning waste, only 3% to inefficiency of the cleaning process, 48% to inefficiency of the combustion process and 2% to line losses (Gluskoter et al., 2009). So, it is extremely important to maintain the constant values of the basic quality parameters of coal delivered to thermal power plants and, also, to precisely defined tolerances of these parameters (Harikrishnan et al., 2016).

The lower quality of coal, in addition to reducing the efficiency of boiler in thermal power plants, imposes other problems: complex disposal requirements of ash and slag, transport of large quantities of materials, environmental problem (air quality, soil, etc.). This problem is often viewed one-sided, i.e., from the aspect of coal recovery from the deposit, without considering the consequences that lower quality coal has in the combustion process. Relating to this, homogenization is one of the ways to solve these problems. However, although the process of homogenization makes uniform the quality of coal, the problem is not solved, because the impurities presented in the coal for combustion to the thermal power plant are not removed this way. A serious analysis of that problem is necessary, especially from the aspect of mineral processing.

Coal processing before combustion significantly affects the reduction in generation of fly and bottom ash, by-products of flue gas desulfurization and other pollutants generated during coal combustion. Cleaning or preparing of coal is most often carried out on the mine site prior to the transport to the thermal power plant and represents the first step in the entire energy cycle. Several technical and prefeasibility studies have evaluated the possibility and viability of pre-combustion of lignite cleaning in Serbia, but none of the proposed and promising processes were not implemented in practice. The aim of this paper is to consider the needs for cleaning of lignite as burning coal and to point out the advantages and importance of cleaning of our coals, or individual parts of the coal deposits before combustion in thermal power plants. So, in this paper we would like to highlight how a simple dry screening process of coal after primary crushing can provide improved quality regarding ash content and calorific values by removing fine particles containing unwanted impurities.

2 INTERNATIONAL AND DOMESTIC PRACTICE

Related international literature indicates determined trends of the introduction of coal cleaning before combustion in thermal power plants because of several advantages that include improved and more consistent coal quality, lower transport costs, reduced capacity of fuel- associated equipment, lessen deposition, corrosion, erosion, and enhanced net TPP heat rate (Burnard et al., 2014).

According to published data, about 40% of coal is being cleaned in South Africa prior combustion in TPP’s, India at the moment cleans about 30% of coal with the tendency to reach over 60% in the near future by building new capacities, in Russia about 35% of coal is cleaned, while in China about 25% of coal is subjected to cleaning processes before sending to TPP’s (Fedorova et al., 2015; Zhenia, 2013). These data are related to coal that is burned in existing conventional thermal power plants with efficiency considerably lower than in the contemporary combustion technologies (Supercritical, Ultra supercritical, Circulating Fluidized Bed, and Integrated Gasification Combined Cycle).

In the United States, more than 30% of the thermal coal is treated using various coal preparation processes that remove unwanted impurities from coal, such as ash, sulphur and moisture, and increase the calorific value of coal in order to improve overall combustion efficiency of the boiler. Coal preparation greatly depends on the relative proportion and differences of composite particles (coal and waste rock) and it usually impossible to physically separate all the organic matter from inorganic impurities (Gluskoter et al., 2009).

Coals from mines in Serbia, both from underground and surface mining, in the aim to obtain final products are treated by simple processes (crushing and screening) or complex cleaning processes (usually by gravity concentration in a suspension of magnetite or quartz sand or by Parnaby process in autogenous suspension). The selection of the applied process depends on the type of coal and its quality, exploitation capacity, purpose, and quality of the obtained final products (ash content, calorific value, moisture, size fraction, etc.) and other factors. Coals from underground and surface mining, especially from surface mining, intended for combustion in thermal power plants, are not cleaned often. These coals are treated only by simple processes such as crushing and screening, reducing to the appropriate size fraction and then sent to the thermal power plant. In addition to required size fraction, these coals must also satisfy the requirements of thermal power plants for calorific values, ash and moisture contents.

The Tamnava coal preparation plant aims to prepare raw coal from surface mining for combustion in thermal power plants. Due to the nature of the deposit and the structure of the coal layer, selective coal mining at the Tamnava surface mine is difficult. Lignite i.e., burning coal from mass coal mining sent to the Nikola Tesla thermal power plants in Obrenovac. This coal has lower quality because of presence of high content of clay, quartz sand and other mineral impurities. The new crushing line was introduced aimed at increasing the capacity and obtaining coal of satisfactory size fraction, while the homogenization process was introduced with the aim of making uniform the quality of coal.

In eastern part of the Kolubara coal basin, there are three exploitation fields: Tamnava – East field, whose exploitation has been finished, Tamnava – West field and the Radljevo field. According to data from the exploration works, almost 21% of the coal in the Tamnava Zapadno polje does not satisfy the required quality in relation to lower calorific value (LCV) by the thermal power plants in Obrenovac. The estimated average quality of coal at Tamnava Zapadno polje has a downward trend, consequently at the end of the exploitation it is expected that ash content will be around 18.5% and LCV (Lower calorific value) below 7 GJ/t (Average total sulphur content is less than 0.6%). The same applies to coal from other open pits, where at Južno polje average ash content is expected to increase to over 17.7% and LCV will drop to less than 7 GJ/t and at Radljevo average ash content in coal will increase over time to over 19% and LCV will decrease to below 6.5 GJ/t. This is supported by the fact that in the tender for the construction of the new thermal power plant Kolubara B, the adopted projected values are 18.36% of ash and LCV of 6.7 GJ / t (Rudarski institut, 2011). Today, the situation is especially interesting in certain parts of the deposit where there are significant reserves of coal finely impregnated with tailings. Reserves of this coal are estimated at 10 million tons, and lower calorific value (LCV) is below 6000 kJ/kg, which is significantly lower than the requirements of thermal power plants.

It is clear that coal processing can have an important role in the electrical power supply chain by providing higher-quality fuel for TPP's in Serbia.

3 MATERIALS AND METHODS

For these investigations two representative coal samples were obtained from the open pit mine Tamnava Zapadno polje during excavation of the first withdrawal cut. Raw coals were sent to the plant by belt conveying system and samples were taken from the belt conveyer after crushing to -60 mm. These samples of coal, for thermal power plant in Obrenovac were taken in different periods of time and they were different relating to quality, i.e., ash contents and calorific values, so marked as sample 1 and sample 2. These samples represent burning coal for thermal power plant in Obrenovac.

The samples of coal, marked as sample 1 and sample 2, were screen by dry procedure on laboratory screens with 5 mm opening. Products of screening (oversize fraction -60+5 mm and undersize fraction -5+0 mm) were dried, measured, and prepared for analysis.

4 RESULTS AND DISCUSSION

Results of dry screening of samples 1 and 2 are shown in Table 1 and Table 2, respectively.

Table 1 Results of dry screening of sample 1

Products Size fraction (mm)	Mass %	Ash %	Ash distribution %	LCV GJ/t	LCV distribution %
-60+5 mm	70.4	14.33	57.39	12.31	85.44
-5+0 mm	29.6	25.30	42.61	4.99	14.56
Feed	100.0	17.18	100.00	9.85	100.00

Table 2 Results of dry screening of sample 2

Products Size fraction (mm)	Mass %	Ash %	Ash distribution %	LCV GJ/t	LCV distribution %
-60+5 mm	70.92	21.68	59.59	6.39	83.17
-5+0 mm	29.08	35.85	40.41	3.22	16.83
Feed	100.00	25.80	100.00	5.46	100.00

It can be seen from Table 1 and 2 that oversize products, size fractions -60+5 mm, obtained by dry screening, have both higher calorific values (LCV) than raw coals. Primary crushing of raw low grade coal leads to concentration of waste minerals in fine fractions, which results in the increase of ash content and the decrease of LCV in those fractions. By screening of size fraction -60+0 mm on 5 mm screen about 70% of oversize fraction can be obtained with 14.33% and 21.68% of ashes and LCV of 12.31 GJ/t and 6.39 GJ/t. Undersize fraction -5+0 mm contained 25.3% and 35.85% of ashes and LCV of 4.99 GJ/t and 3.22 GJ/t. About 85% and 83% of the heat (calorific values) will be separated in the oversize fractions. The screening results clearly indicate that it is possible to achieve satisfactory and continuous coal quality with LCV over 6.10 GJ/t (in the case of low-grade sample 2) for the supply of TPP in Obrenovac, while removing unwanted impurities that concentrates in fine fractions. The presence of tailings is evident in undersize fractions (-5+0 mm) due to the higher ash content and significantly less calorific values in relation to raw coal. It is possible to remove by screening about 30% of coal (in undersize fractions).

5 CONCLUSION

World experience shows that coal cleaning significantly affects different aspects of coal combustion in thermal power plants, among which are the efficiency and performance of the combustion process, the costs of maintenance and transport of coal, disposal of waste materials generated by combustion and mitigation of environmental degradation, especially air pollution. In addition to increasing the reliability of the operation of the thermal power plant, better and uniformed fuel quality enables the higher production of electricity with the same amount of coal due to higher calorific value, which can cover the costs of coal cleaning. It also significantly reduces the pollution of the environment both in terms of the amount of suspended particles and gases with greenhouse effects that are emitted into the atmosphere.

Simple experimental tests have shown that it is possible to successfully clean lignite i.e., burning coal of size fraction -60+0 mm from the Tamnava Zapadno polje in Mining basin Kolubara. Cleaning of burning coal is performed by screening as simple process. According to the distribution, about 83-85% of heat and about 57-59% of ashes will be separated in these products. In this way, it is possible to remove by mass about 30% of coal (in undersize fraction) as tailings. Taking into consideration that tailings in lignite are consisted of mineral impurities, mainly quartz sand and clays, these impurities could be removed in industrial conditions by simple and cheap processes: quartz sand by previous dry screening on vibratory screen, and clays by wet processes (disintegration, desliming and washing). Removal of these impurities can be done in the process of coal preparation and before the crushing. In industrial conditions, it is not realistic to expect that all amount of coal could be cleaned, but individual parts of coal layers in deposit where it is not possible to selectively excavate tailings, could certainly be subjected to some cleaning process, i.e., coal could be planned for cleaning. This solution requires minimal investment in vibratory screens, wastewater thickener and allocation of space necessary for disposal of fine fraction, which share will go up to 30%. To be more precise, Tamnava coal preparation plant with annual capacity of over 16 million tons can treat, with minor reconstruction, the low-grade portions of coal thus removing up to 4.8 million t/yr of coal with LCV slightly over 3 GJ/t.

Considering the results of these tests, it is obviously that cleaning of coal from the surface mining is becoming a necessity, and not just one of the possibilities.

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Original scientific paper

GAS-LIFT WELLS OPTIMIZATION AT THE OIL FIELD "K"

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Abstract: Optimization the operating parameters of a group of gas-lift wells in an oil field is a complex procedure. It is important to match parameters such as gas compression pressure, gas injection pressure, separation pressure at the gathering station, diameters of distribution pipelines, injection gas quantities as well as all individual operating parameters of the gas-lift wells.

In this paper, a model for determining the optimum gas injection rate was created. Also, it is described the procedure for gas-lift well optimization at the oil filed "K" and its results. For all five wells, the optimum amount of injected gas and required number of gas-lift valves were determined.

Keywords: Oil well, Gas distribution, Gas-lift, Optimization

1 INTRODUCTION

In the past period, the prices of natural gas and energy were significantly lower than today. For this reason, it was not so important how much of injected gas was used in order to maximize the oil production rate. Optimization of gas-lift conditions is achieving the maximum possible oil production rate, regardless of the injected gas volume (Brown, 1980). The significant increases in energy demand and natural gas prices have completely changed this situation, so now the optimum conditions for gas injection are based on the economic parameters. (Takacs, 2005).

The main objective of the oil production process is to obtain the optimum oil production while operating costs are minimized (Danilović et al., 2016a; Danilović et al., 2016b). During oil production by gas-lift wells, the gas processing and gas compression represent a significant cost. In order to reduce costs and enable the maximum oil production rate, it is crucial that the compression pressure and the quantity of injected gas be minimized. Defining the optimum parameters of the gas-lift wells, it can be determined the adequate volume of gas injection (Danilović et al., 2016b).

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The proper distribution of the amount of gas injection for two or more gas-lift wells within one gathering station is important part in production optimizing process since the production of each well depends on the injection gas rate.

Based on published model for the distribution of gas for several wells (Danilović et al., 2014), gas-lift curve, gradient curves and cumulative curve will be calculated in this paper, in order to determine the optimum operating parameters of the gas lift wells.

2 DETERMINING THE OPTIMUM AMOUNG OF GAS INJECTION

The gas-lift curve represents the relationship between quantity of gas injection and oil production rate (Figure 1). Gas-lift curve is determined based on the inflow performance relationship (IPR) curve and the vertical lift performance (VLP) curves (Shedid and Yakoot, 2016). Vogel's method is used to calculate the IPR curve, since a single pressure and production measurement was available. Each intersection points of IPR and VLP represents one point of the gas-lift curve. At the beginning, the gas injection rate directly affects on increasing the amount of oil produced (Figure 1 – curve A). Further increase of gas injection rate caused a slight upward trend of oil production rate (Figure 1 – curve B). Since the diameter of the tubing is limited, further increase of injected gas begins to negatively affect the oil flow, primarily due to significantly worse rheological characteristics, i.e., oil density and viscosity. Additional buildup of injection rate result in extremely small increase (Figure 1 - curve C) or a reduction of oil production (Figure 1 - curve D). The optimum amount of gas injection is represented by curve B (Soleša, 2003).

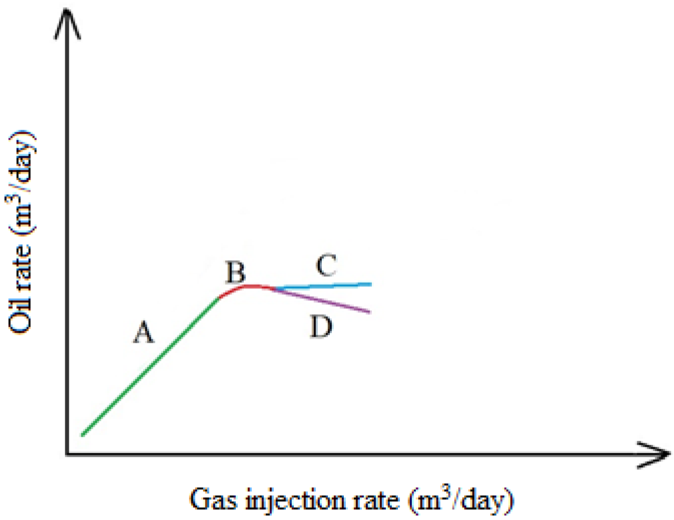

Figure 1 The gas-lift curve

The gas-lift curve is fundamental to design the optimum amount of gas injection. Mathematically analyzing, the maximum value of the function can be determined based on the first derivative of the function. By applying the previous step, the gas-lift curve can be approximated by the appropriate function that represents the quantity of gas injection, then find its first derivative and determine the maximum value that will represent the optimum amount of gas injection. The amount of injecting gas can be approximated by various functions such as polynomial, logarithmic, exponential, and linear function, with a polynomial function being the most adequate (Saepudin et al., 2007).

From a practical point of view, a polynomial of the third degree is satisfactory and the easiest to solve (Vieira, 2015), since after derivation, a polynomial of the second degree (a quadratic equation) is obtained, which can be quickly and easily solved.

In this paper, a model for determining the optimum gas injection rate was created. During the first phase, the gas-lift curve is determined. In the next step, the gas-lift curve is approximated with different polynomial functions. Based on the functions thus determined, the one that best approximates the amount of gas injection is chosen.

For the selected function, the first derivative of the function and its maximum value, which represents the optimum value, are required. Figure 2 shows a simplified algorithm of the developed model for determining the optimum quantity of gas injection.

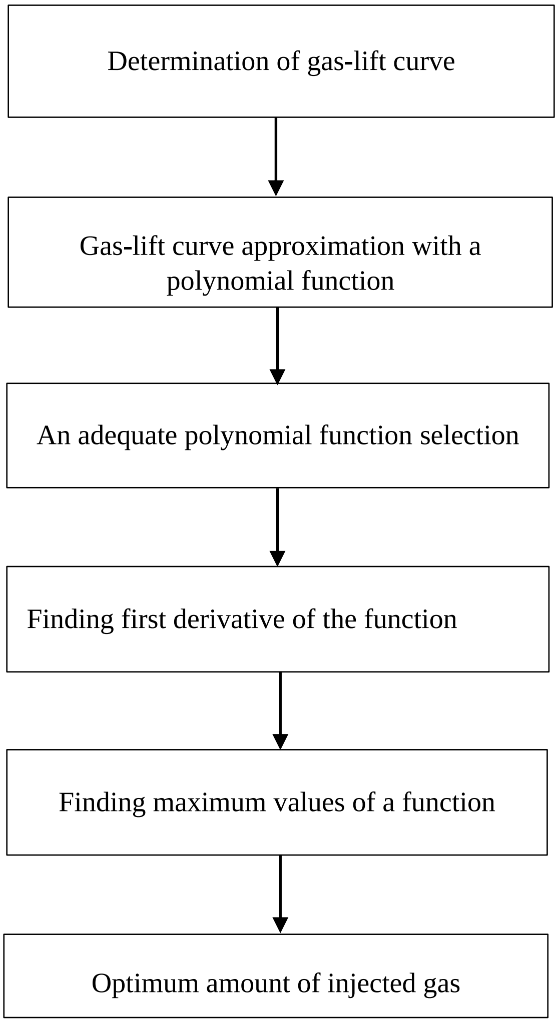

Figure 2 Model for determining the optimum amount of gas injection

3 GAS-LIFT WELLS′ OPTIMIZATION – CASE STUDY

In this field, oil production through four collecting stations KI, CPF (Central processing facility), KW and KS (Figure 3) is carried out. In addition to the oil production, the final preparation of the fluid and gas compression at the gathering station CPF is performed.

Determining the optimum amount of gas injection will be shown in the example of the gathering station KI, which has five gas-lift wells in operation.

For the purpose of making the production process more efficient, the operation of the gas-lift system was optimized.

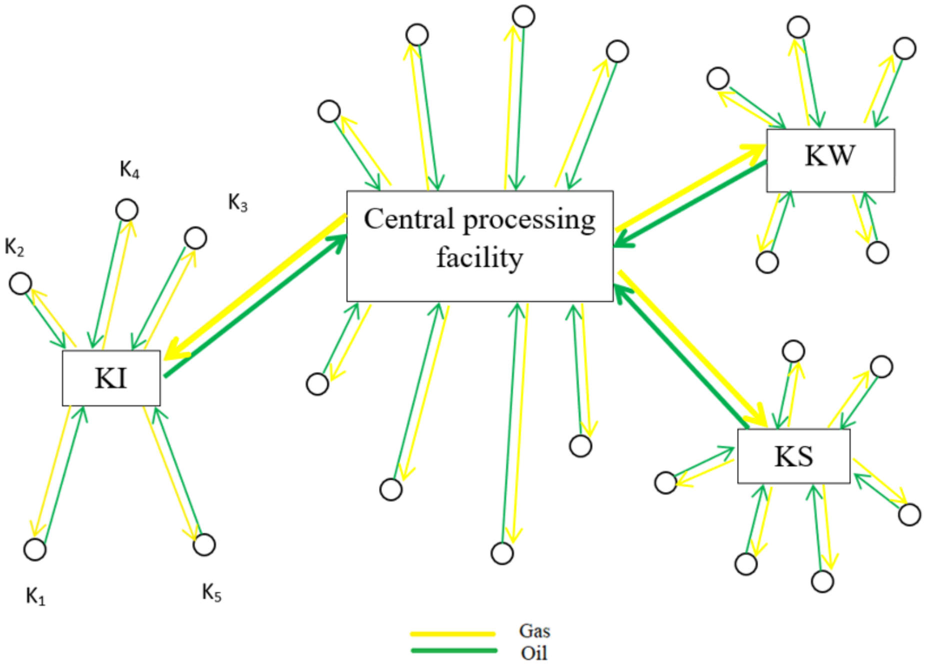

Figure 3 Schematic of gathering stations

The wells′ data are given in Table 1.

Table 1 Wells′ data

	Wells				
	K_1	**K_2**	**K_3**	**K_4**	**K_5**
Well depth (m)	1540	1560	1620	1580	1650
Reservoir pressure (bar)			110,4		
Flowing pressure (bar)	85	91	89	90	95
Oil production (m^3/day)	5,2	8,3	6,5	7,8	9,2
Injection pressure (bar)			29		
Wellhead pressure (bar)			5		

During the first step, the gas-lift curve for wells K_1, K_2, K_3, K_4 and K_5 is calculated (Figures 4, 5, 6, 7 and 8). For gas-lift curve determination it is required to calculate the inflow performance relationship curve (IPR) and vertical lift performance curves (VLP) for various values of the gas oil ratio (GOR).

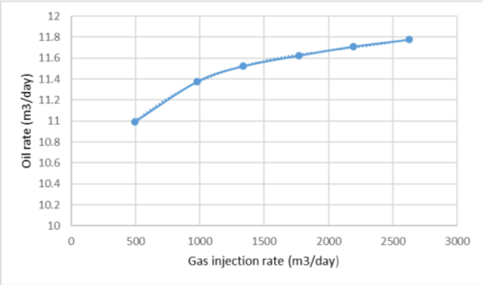

Figure 4 The gas-lift curve for well K_1

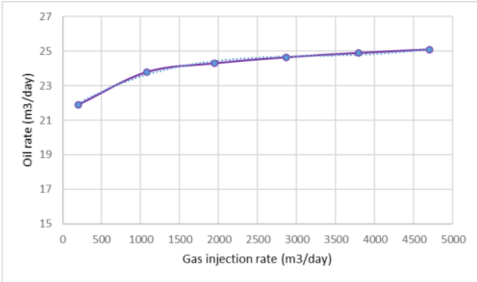

Figure 5 The gas-lift curve for well K_2

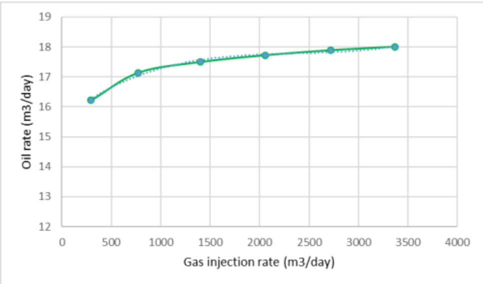

Figure 6 The gas-lift curve for well K_3

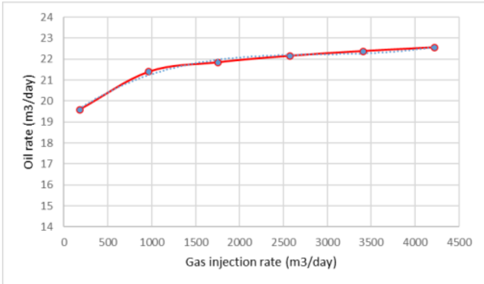

Figure 7 The gas-lift curve for well K_4

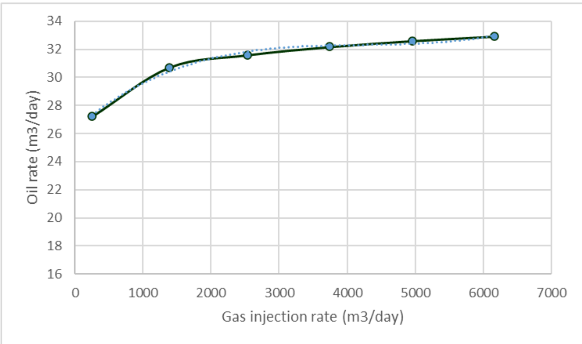

Figure 8 The gas-lift curve for well K_5

In the next step, the limited quantity of gas is distributed to five wells. Based on mathematical model (Danilović et al., 2014; Elhaddad, 2015), the gradient curves for wells K_1, K_2, K_3, K_4 and K_5 were calculated and shown in Figure 9. The cumulative curve (Figure 9) based on which gas can be distributed to individual wells, is obtained by adding the gradient of the curves.

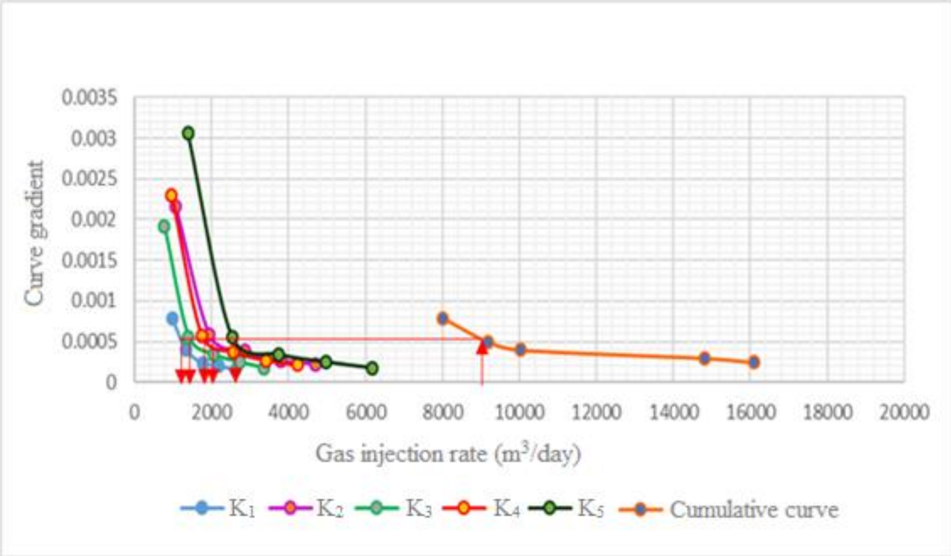

Figure 9 Gradient curves for wells K_1, K_2, K_3, K_4 and K_5 and cumulative curve

Gas distribution to wells K_1, K_2, K_3, K_4 and K_5 is carried out according to the inflow performance relationship curve using cumulative curves. At the gathering station KI, 9000 m^3/day of gas was distributed to five wells. Based on the gradient curve and the cumulative curve (Figure 9), the gas injection rate per well is determined: 1200 m^3/day (K_1), 2000 m^3/day (K_2), 1450 m^3/day (K_3), 1850 m^3/day (K_4) and 2500 m^3/day (K_5).

By approximating the gas-lift curve (Figures 4, 5, 6, 7 and 8) with a polynomial function of the third degree, and finding the first derivative of the function, the optimal production for each well was determined (Table 2).

Table 2 Polynomial function of the third degree

Well	**Equation**	**Optimum production (m^3/day)**
K_1	$y = 10^{-10}\cdot x^3 - 7\cdot 10^{-7}\cdot x^2 + 0{,}0016\cdot x + 10{,}354$	11,4
K_2	$y = 9\cdot 10^{-11}\cdot x^3 - 9\cdot 10^{-7}\cdot x^2 + 0{,}0029\cdot x + 21{,}407$	24,0
K_3	$y = 2\cdot 10^{-10}\cdot x^3 - 10^{-6}\cdot x^2 + 0{,}0026\cdot x + 15{,}583$	17,2
K_4	$y = 10^{-10}\cdot x^3 - 10^{-6}\cdot x^2 + 0{,}0031\cdot x + 19{,}111$	21,5
K_5	$y = 8\cdot 10^{-11}\cdot x^3 - 10^{-6}\cdot x^2 + 0{,}0041\cdot x + 26{,}364$	30,8

The calculated optimum operating parameters of the gas-lift system for wells are shown in Figures 10, 11, 12, 13 and 14 such as valve opening and closing pressure, injection pressure, set pressure, valve depth, liquid level line and gradient line. The gas lift is designed using the injection pressure reduction method.

The number of gas-lift valves is determined so the well unloading process takes place smoothly and that the operating gas-lift valve in the well is at least 150 m below the dynamic fluid level.

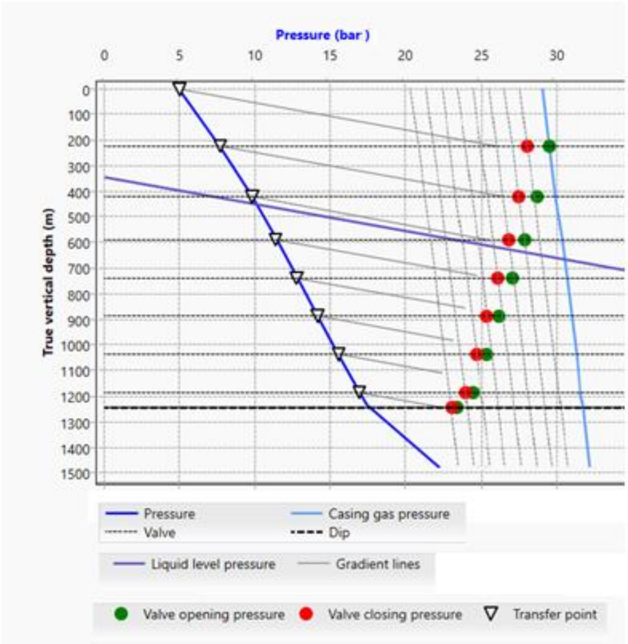

Figure 10 The gas-lift design for well K_1

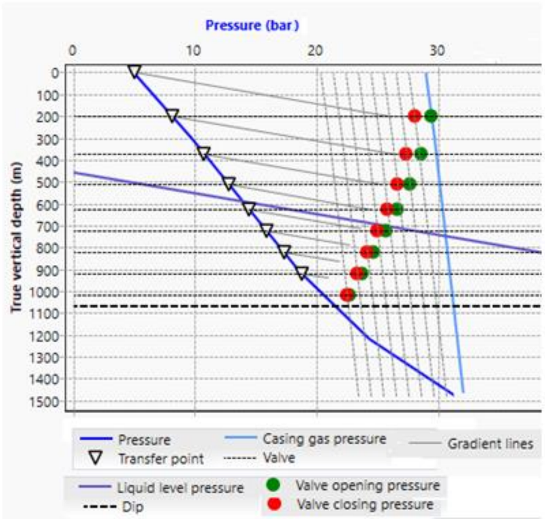

Figure 11 The gas-lift design for well K_2

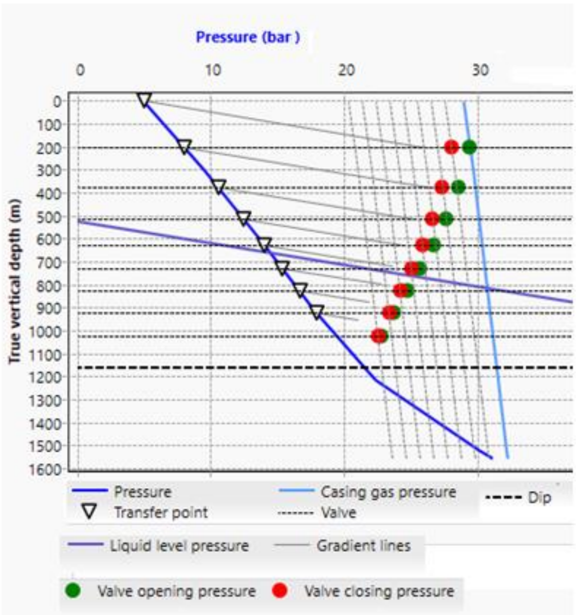

Figure 12 The gas-lift design for well K_3

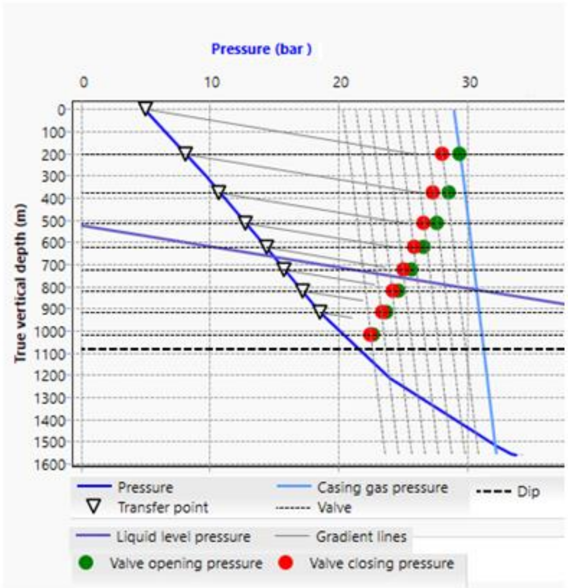

Figure 13 The gas-lift design for well K_4

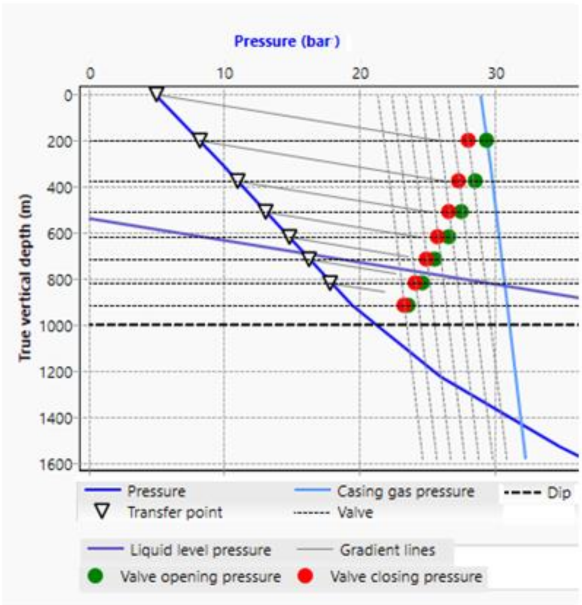

Figure 14 The gas-lift design for well K_5

Numbers and depth of gas-lift valves for each well are shown in Table 3. Wells K_1 to K_4 have eight gas-lift valves each while well K_5 has seven gas-lift valves.

Table 3 Numbers and depth of gas-lift valves

		Wells				
		K_1	**K_2**	**K_3**	**K_4**	**K_5**
Number of valves		**8**	**8**	**8**	**8**	**7**
Depth of gas-lift valve	L_1 (m)	220	200	199	202	200
	L_2 (m)	425	370	385	377	372
	L_3 (m)	590	510	505	508	508
	L_4 (m)	730	614	616	620	616
	L_5 (m)	880	715	720	721	714
	L_6 (m)	1035	820	815	812	812
	L_7 (m)	1190	910	917	916	911
	L_8 (m)	1245	1020	1018	1014	

4 CONCLUSION

The distribution of the gas quantity in several wells is very important in order to achieve optimum production of wells and the operation of the gas-lift system. This is especially important if there is a limited quantity of gas that is injected into the wells.

In this paper, a model for determining the optimum gas injection rate based on the first derivative of the gas-lift curve function was created.

The practical application of the model is shown in the example of the oil field K. Within one gathering station KI on oil field K, where there are five exploitation gas lift wells, the amount of gas injection into each well was calculated (1200 m^3/day (K_1), 2000 m^3/day (K_2), 1450 m^3/day (K_3), 1850 m^3/day (K_4) and 2500 m^3/day (K_5)). The optimum number of valves for each well was determined, as well as the installation depth.

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Original scientific paper

EXAMINATION OF THE POSSIBILITY OF OBTAINING PYRITE CONCENTRATE FROM THE FLOTATION TAILINGS OF THE LECE MINE

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Abstract: The Lece mine is characterized by the fact that it has gold and silver besides the main valuable components in the flotation concentrates of lead and zinc. Practically since the opening of the mine and flotation, research has been carried out with the aim of obtaining better technological indicators on all four valuable metals (lead, zinc, gold and silver), especially on gold. This paper represents a contribution to that research in order to increase the recovery of gold in flotation concentrates. Gold occurs in ore in several ways (native, with lead and zinc, with pyrite and quartz), which requires a complex technological scheme of gold valorization. Most of the gold is bound to galena and is valorized through lead concentrate. A smaller part of the gold is bound to zinc and is valorized through zinc concentrate. However, about 25% of the gold remains in tailings. Researchers ie. the authors of this paper tried to valorize part of the gold that is lost in the tailings by introducing a third pyrite concentrate with an increased gold content.

The paper presents the results of laboratory experiments on the possibility of obtaining pyrite concentrate from the Lece tailings and a proposal for a technological scheme of the process.

Keywords: Lece mine, Flotation, Pyrite concentrate, Gold, Silver

1 INTRODUCTION

Lead concentrate with gold is the most important for the Lece mine, so the most changes were made in this domain in order to improve the technological indicators of the process. The selection of the best flotation machines was performed, so at the end of 2020, a new lead mineral flotation line was put into operation.

Currently, 8 cells RCS-5 are in use for rough and scavenger lead mineral flotation and 4 RCS-3 cells are in use for cleaning lead rough concentrate (Lazić, Nikšić, Stojanović, 2021). The manufacturer of flotation cells is Metso Minerals from Finland. The currently

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installed flotation machines have modern technical and technological characteristics, with accompanying equipment for automatic pulp level control and air consumption. Russian machines installed in 1976 are still in use for zinc mineral flotation.

After the reconstruction, the old line for flotation of lead minerals remained out of use, which can be used for flotation of pyrite minerals, if laboratory experiments show that this is possible.

Hereinafter, a description of the minerals that occur in the deposit is given as a basis for considering the possibility of extracting the third concentrate in the Lece flotation.

In the following text, there is a description of the laboratory experiments of tailings flotation sampled in an industrial plant, a conclusion and a proposal for a technological scheme for flotation of all three minerals (lead, zinc and pyrite).

2 MINERALS THAT OCCUR IN THE LECE DEPOSIT

The ore of the Lece deposit consists of sulphide minerals and quartz. The number of mineral species is relatively small. Ore minerals in the open part of the deposit were formed at low temperatures. These minerals include sphalerite, galena, pyrite, chalcopyrite, and gold-bearing quartz (Jelenković et al. 2010).

Sphalerite is one of the most widespread and abundant sulphide minerals in the deposit, formed at temperatures below 130 ^{o}C. It rarely appears in large crystals; it is mostly fine-grained and contains cadmium.

Galena together with sphalerite is the most important mineral in the deposit. The largest mass of galena is fine-grained in the form of crystals and mineral aggregates. Galena is formed in three phases, the largest part of galena belongs to the third phase, less to the second, and the least to the first phase. The galena of the second and third phases is undifferentiated, forms crystalline masses and nests and contains gold and silver, such galena is called gold-bearing galena. Galena replaces older minerals, and galena is most often replaced by pyrite. It is cracked and catalyzed, in the oxidation zone it is covered with a thinner or thicker crust of cerussite (Radosavljević et al. 2012).

Pyrite is distributed in the deposit in the form of granular aggregates of rounded shape, which indicates formation from gel. Pyrite is often cemented with chalcopyrite, which partially replaces it. He carries some gold and silver.

Chalcopyrite is a carrier of copper and occurs in the ore in small amounts, but it is always present.

Gold occurs in the ore as native. It is found in galena, sphalerite, pyrite, and quartz and shows rounded forms.

3 LABORATORY FLOTATION EXPERIMENTS OF PYRITE FROM MINE TAILINGS LECE

Tailings from the Lece mine flotation process contain from 0.08 to 0.12% Pb, about 0.15 to 0.20% Zn, about 0.6 g/t Au and about 2.2 g/t Ag.

According to the distribution, the metal loss in tailings amounts to about 8-10% for lead and zinc, about 22-25% for gold and about 20% for silver (Lece, 2020).

Such "high losses of gold and silver" in tailings deserve special attention and at the same time offer the possibility of improving technological indicators. This paper is the result of detailed research into the possibility of "production" of the third concentrate in "Lece" flotation - a pyrite concentrate with an increased content of gold and silver.

At the exit from the existing flotation process, the pH of the pulp is about 9.5-10, and for the pyrite flotation process, the recommended pH is about 7 - 8 (Drakšić, 1986; Ćalić, 1990). $FeSO_4$ was chosen as a reagent for lowering the pH of the flotation pulp. This reagent is the safest to work in the plant, and in the flotation pulp it have double action as a pH regulator and as a reagent that "washes" the pyrite surfaces from residual reagents from the previous stage of the process.

$CuSO_4$ was added as a pyrite activator in the pulp conditioning cycle before the pyrite flotation process, and potassium amyl xanthate KAX as colector and Dowfroth-200 (D-200) as frother.

The complete reagent regime of pyrite flotation, which was applied in a series of experiments and two pyrite flotation balances where the best results were obtained are shown in further text.

Reagents regime and flotation conditions of Lece tailings in order to obtain pyrite concentrate

A sample of Tailings from Lece flotation (August-22)

A sample, kg 1

Fineness of grinding, % - 74 μm 55.21

Conditioning min. FeS_2

$FeSO_4$, g/t	1500
$CuSO_4$, g/t	150
KAX, g/t	100
D-200, g/t	10
Conditioning time, min	5
pH	7.1

Rough flotation min. FeS_2

5 min. flot. KAX, g/t	100
Flotation time, min	10

Scavenger flotation min. FeS_2

KAX, g/t	50
Flotation time, min	10

I Cleaning min. FeS_2

D-200, g/t	5
pH	7.5
Flotation time, min	4

II Cleaning min. FeS_2

D-200, g/t	5
pH value	7.5
Flotation time, min	3

III Cleaning min. FeS_2

D-200, g/t	5
pH value	7.5
Flotation time, min	2

Flotation concentration balances of tailings from the Lece mine and production of pyrite concentrate

Table 1 Experiment 1 balance

	T%	Pb%	Zn, %	Au g/t	Ag g/t	R%Pb	R%Zn	R%Au	R%Ag
Tailings 1	100.00	0.09	0.13	0.60	2.22	100.00	100.00	100.00	100.00
C/FeS_2	1.99	0.51	0.82	**9.08**	**49.53**	11.06	12.64	**29.83**	**44.32**
M_1/FeS_2	2.48	0.37	0.37	1.82	9.53	10.03	7.13	7.47	10.66
SC/FeS_2	1.74	0.38	0.55	2.37	12.15	7.21	7.42	6.81	9.51
PK/FeS_2	6.20	0.42	0.56	4.30	23.06	28.29	27.18	**44.12**	**64.49**
Tailings 2	93.80	0.07	0.10	0.36	0.84	71.71	72.82	55.88	35.51

Table 2 Experiment 2 balance

	T%	Pb%	Zn,%	Au g/t	Ag g/t	R%Pb	R%Zn	R%Au	R%Ag
Tailings 1	100.00	0.10	0.18	0.61	2.14	100.00	100.00	100.00	100.00
C/FeS_2	2.00	0.61	0.85	**9.00**	**42.26**	12.78	9.56	**29.28**	**39.34**
M_1/FeS_2	2.49	0.32	0.37	1.63	7.64	8.38	5.20	6.63	8.89
SC/FeS_2	2.74	0.37	0.44	2.83	11.7	10.66	6.80	12.66	14.98
PK/FeS_2	7.23	0.42	0.53	4.12	18.73	31.81	21.56	**48.57**	**63.21**
Tailings 2	92.77	0.07	0.15	0.34	0.85	68.19	78.44	51.43	36.79

The balance sheets did not show the sulfur content in the pyrite concentrates, but it ranged from 46.5 to 47.5% S with a sulfur recovery of about 50 to 60%. Pyrite concentrate with these sulfur contents is not a "standard pyrite concentrate" (more than 48% S is required) but considering that it contains gold and silver and that the quality is very close to standard, the obtained pyrite concentrate certainly deserves attention.

4 TECHOLOGICAL SCHEME OF THE PROCESS OF PYRITE CONCENTRATE PRODUCTION

The scheme of the technological process of pyrite production is shown in Figure 1. The flotation underflow of Pb-Zn ore from the existing flotation (current tailings) is subjected to a conditioning process with the addition of ($FeSO_4$). The role of ferrous sulfate is to lower the pH of the pulp to about 8, to "wash the pyrite surfaces" and prepare for the activation process. Activation of pyrite was performed using ($CuSO_4$) and collection was performed using potassium amylxanthate KAX. Dowfroth 200 (D-200) it was used as a frother. The process of rough and scavenger flotation with three-stage cleaning of the rough pyrite concentrate follows after conditioning. The applied scheme of the technological process and the reagent regime yield a definitive pyrite concentrate of significant quality (911 Metallurgist, 2016).

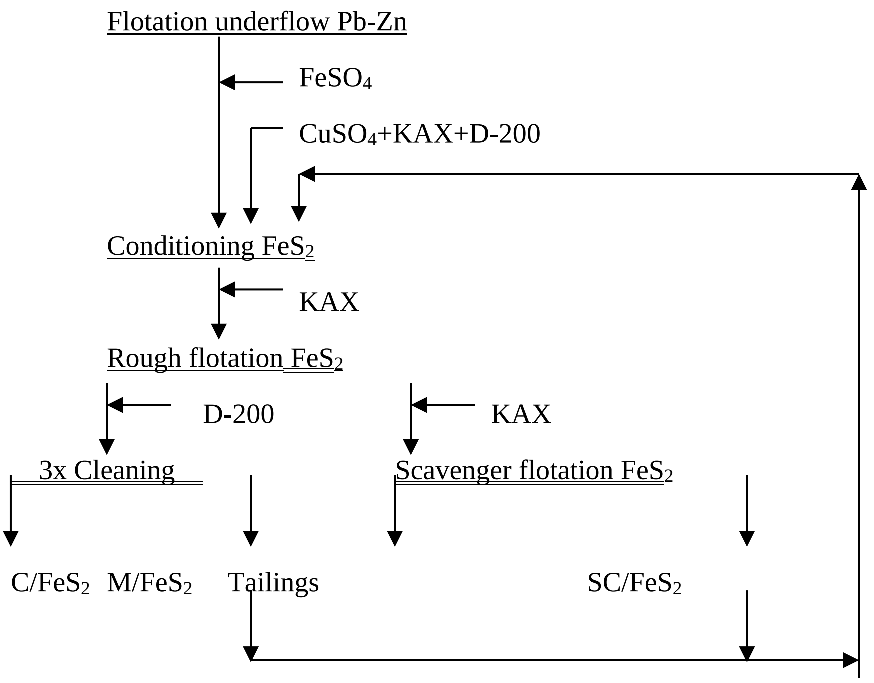

Figure 1 Technological scheme of the process of pyrite concentrate production

5 CONCLUSION

Based on the results presented in this paper, the following can be concluded:

The loss of gold in the current tailings of about 25% deserves special attention. Given that part of the gold is bound to pyrite, and that there is a free line for flotation in the

"Lece" flotation, an attempt was made to obtain pyrite concentrate on that line, as the third product of flotation plant.

The presented results of laboratory tests show that with the applied reagent regime and technological scheme, it is possible to obtain an interesting pyrite concentrate with a sulfur content of about 47% S, sulfur recovery of about 50-60%, with a gold content in this concentrate of up to about 9 g/t and silver of about 40-50 g/t. The recovery of gold from tailings about 30% and silver about 40%.

Given that the loss of gold in the current Pb-Zn flotation tailings is about 25% and that the recovery of gold from that tailing through pyrite concentrate is about 30%, under favorable flotation conditions the total recovery of gold can be increased by about 7.5%, which is very good. Similar to this, the loss of silver in the current Pb-Zn flotation tailings is about 20%, and recovery from this tailing through pyrite concentrate is about 40%. The production of pyrite concentrate would increase the total utilization of silver by about 8%.

The research results presented in this paper are encouraging and deserve an industrial trial in order to confirm these results.

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