

## ГЕОТЕХНОЛОГИЯ. ГОРНЫЕ МАШИНЫ

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### Analyzing methods for calculating the output of the KSM-type surface miners at the Elga coal deposit

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#### Abstract

**Introduction.** The outlook is considered for blastless rock and coal mining at the Elga coal deposit when using continuous mining based on rotary conveyor lines and KSM-type cutting and loading machines. The article describes the mining and geological conditions of the Elga coal deposit. The article considers a range of sizes of the Sutterwhite-class rotary mining machines that contains seven models from the KSM (KRUPP Surface Miner) production series for open-pit mining with an output from 700 to 3000 m<sup>3</sup>/h in a solid block or 1250–4000 m<sup>3</sup>/h in soft ground. The article analyzes various methods for KSM-type surface miner output calculation for the conditions of the Elga coal deposit in the Republic of Sakha (Yakutia).

**Results and analysis.** It has been established that the overburden at the deposit is strongly coherent, the machine's output in terms of energy-power indicators ranges from 420 m<sup>3</sup> for conglomerate and up to 850 m<sup>3</sup> for siltstone, which is less than the rated technical output of KSM-2000R for solid rock equal to 1400 m<sup>3</sup>/h. The results of the KSM-type surface miners output calculation by the kinematic factor show that at a rated layer height of 2.9 m, the output of the KSM-2000R was 1138 m<sup>3</sup>/h, and the output of the KSM-2000RM was 1804 m<sup>3</sup>/h. This correlation is maintained for different layer heights. KSM-2000RM has 80 buckets, while KSM-2000R has only 60 buckets, which explains different output. Additionally, the KSM-2000RM depth of cut is 60 mm, which is greater compared to 47 mm of the KSM-2000R depth of cut. The Dombrovsky method for output calculation using the cross-section area of the cut and the bucket feed showed that the result obtained for the hourly output (1410 m<sup>3</sup>/h) coincides with the hourly output of 1400 m<sup>3</sup>/h specified in the technical passport for KSM-2000R.

**Conclusions.** The results analysis showed that the highest output indicator of 1410 m<sup>3</sup>/h for the KSM-2000R was obtained through the Dombrovsky method, and the output indicator of 1804 m<sup>3</sup>/h for the KSM-2000RM was obtained through the calculation by the kinematic factor.

**Keywords:** cutting force; overburden; surface miner; rock strength; output; cross-section area of the cut; energy intensity; arc excavation.

**Introduction.** Worldwide, including the CIS countries, and in Russia, blastless technology based on continuous miners (rotary conveyor lines) is used in sheet deposits opencast mining. At present, Wirtgen, VASM, and KSM seam-by-seam surface miners have found wide application [1–6]. These machines are capable of mining rock masses with the uniaxial compressive strength of up to 120 MPa with a wide selection of thin layers without preliminary drilling and blasting or mechanical preparation for excavation.

Paper [7] analyzed the engineering solutions in the design of foreign mining machines for underground mining of potash ore.

The Elga coal deposit, which is the largest in the world, is currently being developed in South Yakutia [8]. Due to its huge mineral reserves of high value, it is extremely promising for the Far East.

Commercial coal content is associated with the deposits of the Neryungrikan and Undytkan coal formations. The total thickness of the coal-bearing series is about 200 m. Twenty-two coal seams possess working thickness, five of them are thick with an average thickness of 5 to 10 m. These seams contain about 90% of the deposit's total coal reserve. Most coal seams are of a complex structure and flat dip (2–5 degrees). The beds include from 1–2 to 10–12 rock sheets, represented by carbonaceous siltstones and carbonaceous mudstones, siltstones, fine-grained sandstones, and less often medium-grained sandstones.

Continuous mining based on rotary conveyor lines and KSM-type cutting and loading machines is a promising technology in terms of selective mining.

**Materials.** The German company KRUPP has created a range of sizes of the Sutterwhite-class rotary surface miners that contains seven models from the KSM (KRUPP Surface Miner) production series for open-pit mining with an output from 700 to 3000 m<sup>3</sup>/h in a solid block or 1250–4000 m<sup>3</sup>/h in soft ground (Table 1) [9].

**Table 1. Technical characteristic of surface miners of Krupp Fordertechnik**  
**Таблица 1. Техническая характеристика комбайнов фирмы «Крупп Индустритехник»**

Indicator	Model of a surface miner			
	KSM-1000	KSM-2000	KSM-2000K	KSM-4000
The rated output, m <sup>3</sup> /h, in a solid block	700	1400	1400	2800
The diameter of a work tool, m	3.20	3.55	3.55	3.85
The greatest height of the seam being cut, m	2.20	2.50	2.50	2.75
The width of cut (line), m	4.35	5.60	5.60	7.10
The speed of travel under the rated output, m/min	1.2	1.8	1.8	2.4
The mass of the machine, t	120	190	210	380
The overcomable longitudinal gradient, degrees, when operating	7	–	7	–
when travelling	10	–	10	–
The possible transverse gradient, degrees, when operating and travelling	6	–	6	–

Soon afterwards the KRUPP company and the Skochinsky Institute of Mining developed the KSM-2000R miners for the conditions of coal deposits in Kuzbass, Eastern Siberia and similar regions [10].

The machine has a wide-cut work tool in its front part and excavates rock with the Protodyakonov hardness ratio of 2 to 8 without preliminary drilling and blasting. The rated output of the KSM-2000R is 2000 m<sup>3</sup>/h for soft ground (1400 m<sup>3</sup>/h for a solid block). An open-pit bench is mined using the seam-line extraction technology.

The main advantages of the KSM-2000R-type surface miners are as follows:

- relatively high cutting forces, 5–6 times as high as of a bucket-wheel excavator,
- a wide range of thickness of the mined seam (from a few centimeters to 2.9 m),
- no auxiliary equipment,
- the possibility to independently driving pit ramps,
- and good maneuverability, up to the ability to make a turn on the spot.

With the same rated output, the mass of the KSM machine is half the mass of the EKG-20 mine excavator [11].

At the N. V. Chersky Institute of Mining of the North SB RAS, it has been established that in the course of  $H_{15}$  and  $H_{15}^y$  complex coal seams selective mining using the KSM-2000R, depending on the extracted seam parameters, the coal dilution will decrease by 1.8–6.5 times, and coal ash content will decrease by 1.3–2.5% compared to bulk mining. During the development of complex-structural seams with numerous rock intercallations, losses will increase insignificantly, while during the development of simple coal seams, losses will decrease significantly [12].



Figure 1. Mining the overburden and coal of the Taldinsky opencast coal mine by the KSM-2000R

Рисунок 1. Отработка вскрышных пород и угля комбайном КСМ-2000Р на угольном разрезе «Талдинский»

Since the introduction of the KSM-2000R at the Taldinsky coal mine in Central Kuzbass in 1996, the technological capabilities of the miner have been repeatedly studied through its energy and power indicators. The tests took place in changing mining and geological conditions in the course of blastless excavation of rocks with the ultimate uniaxial compression strength  $\sigma_{\text{compression}}$  from 25 MPa to 120 MPa (Figure 1). The work tool of the KSM-2000R surface miner has been improved as a result of testing at the Taldinsky coal mine. The number of buckets has been increased from 15 to 20. The modernized surface miner was named KSM-2000RM [13]. The regularities obtained, which characterize the work flow of the KSM-2000R, allow to make reliable prediction about the expected output indicators of these machines in particular mining and geological conditions. Thus, the established relationships between the energy density of the work flow  $H_w$  and the strength of rock make it possible, based on the geological conditions of the deposit planned for mining, to determine the rational energy-power and weight-size parameters of the KSM-type miner [14, 15].

**Methods of research.** Considering the empirical dependence by the force factor between the energy density of excavation and the physical and mechanical properties of mined rock, proposed by the Skochinsky Institute of Mining, main indicators of the KSM-2000R work flow for the bedrocks at the Elga deposit were calculated.

The results of energy-power indicators calculation (energy density  $H_w$ , rock resistivity  $K_f$ , and technical output  $Q_t$ ) of the KSM-2000R operation on the Elga deposit bedrocks are presented in Table 2.

The analysis of the results of energy-power indicators calculation of the KSM-2000R operation on the Elga deposit bedrocks using the the Skochinsky Institute of Mining method showed that the energy density of excavation  $H_w$  for these rocks was 1.35–2.74 kW · h/m<sup>3</sup>. Rock resistivity  $K_f$  varies within 4.35–8.9 MPa, which corresponds to the weighted mean value of rock strength for the seam being cut  $f_{mean} = 4.9–10$  according to the scale by Professor M. M. Protodyakonov. Such high figures were explained by the fact that when developing, for example, conglomerates with the KSM-2000R, their fragility coefficient was 4.6. A decrease in rock fragility coefficient results in the cutting process energy density growth and vice versa: the higher the materials’ fragility, characterized by the ratio of the compressive and tensile strength of rock, the more efficient the excavation process.

**Table 2. The energy-power indicators of the KSM-2000R on the bedrock of the Elga coal deposit (the method by the Skochinsky Institute of Mining)**

**Таблица 2. Энергосиловые показатели работы КСМ-2000Р на коренных породах Эльгинского месторождения (методика ИГД им. Скочинского)**

Name of rock	$H_w$ , kW · h/m <sup>3</sup>	$K_f$ , MPa	The percentage of rocks in an opencast mine (containing the estimated beds), %	The output $Q_t$ , m <sup>3</sup> /h (in a solid block)
<i>Undytkan coal formation</i>				
Conglomerates	2.73	8.90	5.60	420
Gravelstone	1.91	6.21	2.00	600
Coarse-grained sandstones	2.38	7.78	18.40	480
Medium-grained sandstones	2.48	8.13	30.90	460
Fine-grained sandstones	2.34	7.62	20.80	490
Siltstones	1.61	5.23	11.50	710
Coal	0.29	2.70	10.80	1400
<i>Neryungrikan coal formation</i>				
Coarse-grained sandstones	1.88	6.11	10.30	610
Medium-grained sandstones	1.81	5.91	18.90	630
Fine-grained sandstones	2.11	6.91	26.40	540
Siltstones	1.35	4.35	24.80	850
Coal	0.15	1.85	19.60	1400

The obtained calculations showed that the overburden of the Elga deposit is very strongly coherent, the machine’s output varies within 420 m<sup>3</sup> for conglomerates and up to 850 m<sup>3</sup> for siltstones, which is lower than the rated technical output of the KSM-2000R for a solid block which is equal to 1400 m<sup>3</sup>/h.

For KSM-2000R and KSM-2000RM miners, the Skochinsky Institute of Mining also obtained the dependence between the value of technical output, m<sup>3</sup>/h, by the kinematic factor. This factor considers the geometry of the miner’s work tool, which directly affects the height of the seam being cut and the depth of cut directly:

$$Q_t \leq \frac{60BHt_{cut} n_{work\ tool} z_0}{z_{cutters} \sin \left[ \arccos \left( 1 - \frac{H}{R_{work\ tool}} \right) \right]}, \tag{1}$$

where  $B$  and  $H$  are the width of the line being cut and the height of the seam, m;  $t_{cut}$  is the maximum depth of cut, m;  $n_{work\ tool}$  is the speed of the work tool rotation, r/min;  $z_0$  is the number of cutting edges on each bucket wheel of the work tool, units;  $z_{cutters}$  is the number of cutters in the cutting line for each bucket wheel on the work tool, units;  $R_{work\ tool}$  is the radius of the work tool, m.

The results of calculating the value of technical output by the kinematic factor of the KSM-2000R and KSM-2000RM-type miners at different heights of the developed seam for the Elga deposit bedrock by formula (1) are presented in Table 3.

**Table 3. The technical output the KSM-2000R and the KSM-2000RM under different heights of the seam being cut (by the method of the Skochinsky Institute of Mining and by the kinematic factor)**

**Таблица 3. Техническая производительность КСМ-2000Р и КСМ-2000РМ при различной высоте разрабатываемого слоя (методика ИГД им. А. А. Скочинского по кинематическому фактору)**

The model of the surface miner	The height of a seam $h_{seam}$ , m							
	2.9	2.5	2.0	1.5	1.0	0.5	0.2	0.1
KSM-2000R, m <sup>3</sup> /h	1138	1028	888	745	591	404	257	178
KSM-2000RM, m <sup>3</sup> /h	1804	1750	1510	1267	1005	688	438	303

The results of calculations for KSM miners output by the kinematic factor show that at a rated height of a seam of 2.9 m, the KSM-2000R output was 1138 m<sup>3</sup>/hour, and that of the KSM-2000RM was 1804 m<sup>3</sup>/hour. This ratio is maintained for different seam heights. This difference in output is explained by the fact that the KSM-2000RM miner has 80 buckets, while the KSM-2000R has only 60 buckets. The KSM-2000RM combine has a greater depth of cut ( $t_{cut} = 60$  mm) compared to KSM-2000R ( $t_{cut} = 47$  mm).

One of the well-known methods for determining the output is the *Dombrovsky method* for the bucket-wheel excavator output determination [16]. In this method, the output of the excavation machine is determined by the cross-section area of the cut and the bucket feed.

Let us make a calculation for the KSM-2000R surface miner. We calculate the cross-cut area of the cut under the rated seam height  $h_{seam} = 2.9$  m and a wheel diameter  $K_h = 0.63$ .

To determine the number of buckets in operation, let us calculate the arc excavation using the following formula:

$$\varphi_{arc} = \frac{\pi}{2} + \alpha_1, \tag{2}$$

where  $\alpha_1$  is the angle between the buckets.

Considering that

$$\alpha_1 = \arcsin \frac{2(D_{work\ tool} K_h - (D_{work\ tool}/2))}{D_{work\ tool}} = 15 \text{ degrees,}$$

where  $D_{work\ tool}$  is the diameter of the work tool,  $D_{work\ tool} = 4.8$ ;  $K_h = 0.63$ .

Then  $\varphi_{arc} = 105$  deg.

The number of simultaneously working buckets in the ground:

$$n_{working\ buckets} = \frac{\varphi_{arc}}{\alpha} + 1 = 5 \text{ buckets,}$$

where  $\alpha$  is the spacing angle of the buckets,  $\alpha = 360/n_{buckets} = 360/15 = 24$  degrees; where  $n_{buckets}$  is the number of buckets on the bucket wheel.

Let us find the bucket feed  $c_1$  in the horizontal direction by one spacing of buckets  $T$  in a time  $t_0 = T/v_{\text{cutting}}$ , where  $v_{\text{cutting}}$  is the cutting speed. However, the feed is obvious:

$$c_1 = v_{\text{travel}}t_0 \quad \text{or} \quad c_1 = v_{\text{travel}} \frac{T}{v_{\text{cutting}}}, \tag{3}$$

where  $v_{\text{travel}}$  is the travel speed of the miner, m/s.

**Table 4. The main indicators of the KSM-2000R operation under different heights of a seam (the Dombrovsky method)**

**Таблица 4. Основные показатели работы КСМ-2000Р при различной высоте слоя (методика Домбровского)**

Indicator	The height of a seam $h_{\text{seam}}$ , m						
	2.9	2.5	2.0	1.5	1.0	0.5	0.2
The number of buckets taking part in the process of cutting, units	20	16	16	12	12	12	8
The cross-section area of the cut for 1 bucket $F_i$ , cm <sup>2</sup>	132	136	134	127	110	84	45.6
The total cross-section area of cut of all buckets taking part in the process of cutting $F$ , cm <sup>2</sup>	5532	4196	3711	2314	1505	684	183
The output $Q$ , m <sup>3</sup> /h	1410	1072	950	585	385	175	47

According to the data from the KSM-2000R technical passport,  $v_{\text{cutting}} = 1.5$  m/s. We also know the travel speed of the miner  $v_{\text{travel}} = 1.3$  m/s and the number of unloadings  $n_{\text{unloadings}} = 90$ .

**Table 5. The main indicators of the KSM-2000RM operation under different heights of a seam (the Dombrovsky method)**

**Таблица 5. Основные показатели работы КСМ-2000РМ при различной высоте слоя (методика Домбровского)**

Indicator	The height of a seam $h_{\text{seam}}$ , m						
	2.9	2.5	2.0	1.5	1.0	0.5	0.2
The number of buckets taking part in the process of cutting, units	28	24	24	20	16	12	8
The cross-section area of the cut for 1 bucket $F_i$ , cm <sup>2</sup>	132	136	134	127	110	84	45
The total cross-section area of cut of all buckets taking part in the process of cutting $F$ , cm <sup>2</sup>	6125	5124	4532	3657	2113	752	180
The output $Q$ , m <sup>3</sup> /h	1565	1310	1158	934	540	192	46

Considering that the number of unloadings  $n_{\text{unloadings}} = (60 v_{\text{cutting}})/T$ , we get  $T = (60 v_{\text{cutting}})/n_{\text{unloadings}} = (60 \cdot 1.5)/90 = 1$  m. Then  $t_0 = T/v_{\text{cutting}} = 1/1.5 = 0.66$  m/min. Therefore,  $c_1 = v_{\text{travel}}t_0 = 1.5 \cdot 0.66 = 0.86$  m/min.

The cross-cut area of the cut made by each bucket in the cross section under  $h_{\text{seam}} = 2.9$  m will be  $F_i = bc_1 \cos\varphi = 160 \cdot 0.86 \cdot 0.96 = 132$  cm<sup>2</sup>, where  $b$  is the width of a bucket,  $\varphi$  is the angle that determines the position of the bucket relative to the horizontal line through the axis of the bucket wheel.

The cross-cut area of cuts made by all buckets simultaneously depends on the height of a seam, the number of buckets and their angular position. It can be determined based on the formula for one wheel:

$$F = bc_1 h_{\text{seam}} \times (\cos\alpha + \cos(\alpha - \alpha_1) + \cos(2\alpha - \alpha_1) + \dots + \cos((n_{\text{working buckets}} - 1)\alpha - \alpha_1)) = 1383 \text{ cm}^2.$$

Let us find the total cross-cut area of the cuts made by all working buckets:  
 $F_1 = F \cdot 4 = 1383 \cdot 4 = 5532 \text{ cm}^2.$

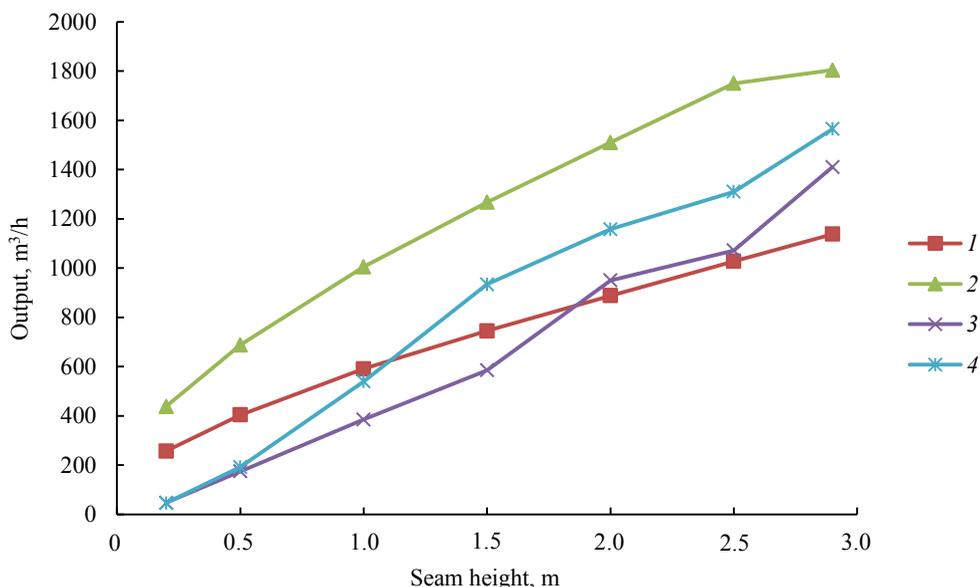


Figure 2. The dependence between the KSM-type surface miner output and the height of the seam being cut: 1 – KSM-2000R by the kinematic factor; 2 – KSM-2000RM by the kinematic factor; 3 – KSM-2000RM and the height of a seam according to Dombrovsky; 4 – KSM-2000R and the height of a seam according to Dombrovsky

Рисунок 2. Зависимость производительности комбайна типа КСМ от высоты разрабатываемого слоя: 1 – КСМ-2000Р по кинематическому фактору; 2 – КСМ-2000РМ по кинематическому фактору; 3 – КСМ-2000РМ от высоты слоя по Домбровскому; 4 – КСМ-2000Р от высоты слоя по Домбровскому

Let us calculate the output of the KSM-2000R by the formula:

$$Q = FBCt = 5532 \cdot 7.1 \cdot 6 \cdot 60 = 1410 \text{ m}^3 / \text{h}, \tag{4}$$

where  $B$  is the width of the face,  $B = 7.1 \text{ m}$ ;  $C$  is the bucket wheel rotation speed,  $C = 6 \text{ r/min}$ ;  $t$  is the excavation time,  $t = 60 \text{ min}$ .

The obtained result of hourly output  $Q = 1410 \text{ m}^3/\text{h}$  coincides with the hourly output of  $1400 \text{ m}^3/\text{h}$  specified in the technical passport for the KSM-2000R.

The results of KSM-2000R output calculation for various heights of the seam being cut for bedrocks of the Elga deposit are presented in Table 4.

Using the same method, let us make a calculation for the KSM-2000RM: the cross-cut area of the cut made under a rated face height  $h_{\text{seam}} = 2.9 \text{ m}$  and a wheel diameter  $K_h = 0.63$ .

The results of KSM-2000RM output calculation for various heights of the seam being cut for bedrocks of the Elga deposit are presented in Table 5.

The cross section of the cut changes and reaches its maximum value at a digging height equal to the radius of the bucket wheel.

The analysis of the obtained results showed that due to a larger number of buckets involved in the cutting process, the output of the KSM-2000RM is 10–18% higher than that of the KSM-2000R.

Comparison of KSM-2000R and KSM-2000RM output indicators is given in Figure 2.

The analysis of the obtained results showed that the highest KSM-2000R output was obtained according to the N. G. Dombrovsky method,  $Q = 1410 \text{ m}^3/\text{h}$ , while the highest KSM-2000RM output was obtained when calculating by the kinematic factor,  $Q = 1804 \text{ m}^3/\text{h}$ .

**Conclusions.** The analysis showed that the highest KSM-2000R output of  $1410 \text{ m}^3/\text{h}$  was obtained according to the N. G. Dombrovsky method, while the highest KSM-2000RM output of  $1804 \text{ m}^3/\text{h}$  was obtained when calculating by the kinematic factor.

Studies have shown that the overburden of the Elga deposit is very strongly coherent, the output of the miner for it is about  $420 \text{ m}^3$  for conglomerates and up to  $850 \text{ m}^3$  for siltstones, which is less than the rated technical output of the KSM-2000R for a solid block equal to  $1400 \text{ m}^3/\text{h}$ .

The output calculation according to the Dombrovsky method considering the area of the cut and bucket feed showed that the result obtained for the hourly output ( $1410 \text{ m}^3/\text{h}$ ) coincides with the KSM-2000R output specified in the technical passport; in a solid block the miner's output is  $1400 \text{ m}^3/\text{h}$ .

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### Анализ методик расчетов производительности комбайнов типа КСМ на Эльгинском месторождении

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#### Реферат

**Введение.** Рассмотрены перспективы безвзрывной разработки пород и угля Эльгинского месторождения при поточной технологии на базе роторно-конвейерных комплексов и погрузочно-выемочных комбайнов типа КСМ. В статье описаны горно-геологические условия Эльгинского каменноугольного месторождения. Рассмотрен типоразмерный ряд роторных комбайнов класса Sutterwhite, состоящий из семи моделей производственной серии для открытых горных работ KRUPP Surface Miner с производительностью от 700 до 3000 м<sup>3</sup>/ч в целике или 1250–4000 м<sup>3</sup>/ч по рыхлой массе. Выполнен анализ различных методик расчета производительности комбайнов типа КСМ для условий Эльгинского каменноугольного месторождения Республики Саха (Якутия).

**Результаты и их анализ.** Установлено, что вскрышные породы месторождения являются весьма крепкими, производительность машины по энергосиловым показателям изменяется в пределах от 420 м<sup>3</sup> по конгломератам до 850 м<sup>3</sup> по алеволитам, что меньше расчетной технической производительности КСМ-2000Р по плотной массе, равной 1400 м<sup>3</sup>/ч. Результаты расчетов по производительности комбайнов типа КСМ по кинематическому фактору показывают, что при номинальной высоте слоя 2,9 м производительность комбайна КСМ-2000Р составила 1138 м<sup>3</sup>/час, а КСМ-2000РМ – 1804 м<sup>3</sup>/час. Это соотношение сохраняется при различной высоте слоя. Такое различие по производительности объясняется тем, что у комбайна КСМ-2000РМ число ковшей – 80 шт., а у КСМ-2000Р – всего 60 шт. Также у комбайна КСМ-2000РМ больше толщина стружки (60 мм) по сравнению с КСМ-2000Р (47 мм). Расчет производительности согласно методике Домбровского по площади срезаемой стружки и подаче ковша показал, что полученный результат по часовой производительности (1410 м<sup>3</sup>/ч) сходится с паспортной производительностью КСМ-2000Р, в плотном теле производительность машины – 1400 м<sup>3</sup>/час.

**Выводы.** Анализ полученных результатов показал, что наибольшие показатели производительности КСМ-2000Р получились по методике расчета Н. Г. Домбровского – 1410 м<sup>3</sup>/час, а КСМ-2000РМ при расчете по кинематическому фактору – 1804 м<sup>3</sup>/час.

**Ключевые слова:** усилие резания; вскрышные породы; комбайн; прочность пород; производительность; площадь стружки; энергоемкость; дуга копания.

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