Розроблено аналітичний метод визначення зношення броні барабана млина з врахуванням його кульового завантаження при розмелюванні вугілля марки «Г». Розроблені рекомендації щодо практичного визначення кульового завантаження млина за експлуатаційною характеристикою $N_м=f(G_к)$ з урахуванням поправки на перевитрату куль, яка компенсує втрату металу броні барабана

Ключові слова: аналітичний метод, паровий котел, кульовий барабанний млин, вугілля, темп зношення броні барабану, темп зношення куль, час роботи млина, кульове завантаження

Разработан аналитический метод определения износа брони барабана мельницы с учетом его шаровой загрузки при помоле угля марки «Г». Разработаны рекомендации по практическому определению шаровой загрузки мельницы по эксплуатационной характеристике $N_м=f(G_к)$ с учетом поправки на перерасход шаров, которая компенсирует потерю металла брони барабана

Ключевые слова: аналитический метод, паровой котел, шаровоя барабанноя мельница, уголь, темп износа брони барабана, темп износа шаров, время работы мельницы, шаровые загрузки

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DEVELOPMENT OF THE ANALYTICAL METHOD FOR DETERMINING THE ARMOR WEAR OF THE DRUM BALL MILL

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1. Introduction

The power industry is one of the basic components of Ukraine's economy, the effectiveness of which contributes to the state progress. The basis of the power industry is the electric power industry, which uses coal as primary power source. About 30 % of the total electric power is produced on coal-fired power plants in Ukraine. Such amount of electric power generation requires efficient combustion of fossil fuel, i. e. coal.

The coal entering a boiler furnace undergoes appropriate preliminary preparation. The fuel is dried and ground in drum ball mills, after which it is fed into the dust hopper, and then in the boiler through the burners.

The efficiency of combustion depends on the quality of the prepared coal dust in drum ball mills, the performance of which deteriorates in the process of operation because of the need to periodically check and adjust the work of the mills.

One of the key operating parameters of a drum ball mill is the drum armor wear and ball charge of a drum, which affect the performance and specific electric power consumption for dust preparation.

During the mill operation, the ball charge is maintained at a constant maximum level by the periodic addition of balls to the drum, which provides the best possible performance with satisfactory quality of the finished dust. According to the characteristic $N_m=f(G_b)$, the operating maximum ball charge corresponds to the mill electric motor loading, which depends on the value of the rotating mass of the drum and balls. In this case, the replacement of the drum armor wear (ΔG_δ) with the value of the ball charge (ΔG_b) increase occurs, which adversely affects the performance of drum ball mills and ultimately the reliability. Therefore, the development of an analytical method for determining the armor wear of the mill drum, taking into account its ball charge, is an urgent task.

2. Literature review and problem statement

Coal-fired power plants are the basic component of the power industry of Ukraine and many countries of the world and occupy one of the main places in electric power generation [1, 2]. Today, Ukrainian thermal power plants produce about 30 % of electric power [3]. In accordance with the development plans of Ukraine's power industry till 2030, TPPs operating on coal of own production will be the basis of flexible power facilities of the united energy system (UES) of Ukraine. It is planned to introduce clean coal technologies, based on the development of new and already known technological processes and to consider the issue of possible coal combustion in a pilot plant [4]. The works [5–7] highlight the issues of fossil fuel combustion and capture of fuel ash particles in flue gases. In the above publications, the authors consider not efficiency, but actual operation of drum ball mills. Ensuring the reliability of boiler units is a key component of efficient operation of TPP power units, as well as operation of drum ball mills and armor surfaces.

It is known that the coal grinding process is accompanied by a simultaneous wear of ball metal and drum armor [8]. Gradual and continuous wear of armor reduces the drum weight, which lowers the electric load N_m and introduces an error when determining the ball charge.

In [9, 10], the problem of the power industry regarding the production of synthesis gas from fossil fuels (coal) is investigated. At the same time, the authors pay attention not to fuel preparation, that is, drying and grinding, but only to the process of synthesis gas production.

The papers [11, 12] investigate the processes of solid fuel gasification and describe the design features of circulating fluidized bed (CFB) gasifiers, and do not consider the coal preparation in ball mills, but take estimated values only.

Modern research works on drum ball mills, as well as regulatory documents, do not specify the rates and periods of armor wear of drums of different manufacturers, but only expenditures of balls [13–15]. The paper [15] describes the experimental studies of dust systems, while analytical methods of research have not been given due attention. Accordingly, this does not allow ensuring cost-effective and reliable operation of drum ball mills.

Experimental methods for determining the performance of drum ball mills are also known [16, 17]. However, the rational and maximum efficiency of the mills can be provided by reliable operation of armor surfaces of mills. At the same time, the recommendations contained in them have either a rather general nature, or, conversely, a very narrow application scope.

Therefore, the development of an analytical method that would allow carrying out diagnostic tests and engineering calculations of dust systems without conducting experimental studies is an important scientific and applied problem.

3. The aim and objectives of the study

The aim of the work was to develop an analytical method and carry out the corresponding calculations of the mill drum armor wear. To achieve this aim, it was necessary to accomplish the following objectives:

– to determine the armor wear of the mills KBM 370/850 (Sh-50A) that grind «G» grade coal;

– to determine the wear rate of the drum armor depending on the manufacturer in Ukraine;

– to determine the ball charge, taking into account the mill drum armor wear and the characteristic $N_m=f(G_b)$ of the mill electric motor loading.

4. Objects and methods of research

4. 1. Objects of research of Burshtyn TPP to develop an analytical method for determining the KBM armor wear

The boiler TP-100 (TP-100A) of the 200 MW power unit of Burshtyn TPP (Ukraine) is equipped with two individual dust preparation systems with drum ball mills KBM 370/850 (Sh-50A).

The dust system of the boilers TP-100 is designed for grinding «G» grade coal of the Lviv-Volyn coal basin (Ukraine): $Q_l^w=24.41$ MJ/kg (5830 kcal/kg), $W^P=7.4$ %, $A^P=22.4$ %, $V^G=38.5$ %; grindability index $I_G=1.2$.

Design parameters of the finished dust: $R_{90}=24$ %, $W^D=2$ %.

Basic elements of the mill KBM 370/850 (Sh-50A):

– rotating horizontal cylindrical drum;

– armor coating of the inner surface of the drum body;

– drum ball charge;

– mill drive – low-speed synchronous electric motor, connected to a drive gear and a gear ring of the drum through a coupling;

– self-lubricating bearings.

In the design, the cylindrical inner surface of the drum is equipped with armored plates, the mounting of which to the case shell is carried out by means of spacer wedges. Plates and wedges form a continuous wave that promotes capture and lifting of balls and coal material. The end walls of the drum are covered with flat armor plates.

Characteristics of ball charge and design armor of the mill drum:

– ultimate ball charge $\tau=100$ t;

– design ball charge $G_b^d=8$ ball 0 t;

– maximum operating ball charge $G_b^{max}=70$ t;

– ball diameter $d=40$ mm;

– design weight of the drum armor plates $G_b^{max}=70$ t;

– estimated specified life of the mill drum armor $T=20000$ h.

The complete replacement of the drum armor is recommended in case of weight reduction up to 50 % of the original design value.

The mills equipped with armor plates, depending on the manufacturer, located in the cities of Donetsk, Bilozersk and Dnipro (Ukraine), have different service life of the drum armor.

The technical measure to increase the life of the drum cylindrical surface armor is the introduction of the rolling sleeper armor, developed by the «Rudmetalurgprom» enterprise (Ukraine) and manufactured by the Dnipro steel works.

4. 2. Methods of research for determining analytical optimization of armor wear of the KBM drum and balls

To perform the experimental part of the work, commonly used methods of heat engineering measurements were used. Modern methods of research and calculation using the physical modeling of a numerical experiment on a computer, methods of experiment planning and mathematical statistics means were used.

5. Results of calculating the mill drum armor wear

Metal loss from the drum armor wear was calculated based on the armor wear rate and duration of the maximum interrepair time of the mill. Thus, the metal loss was calculated in case of replacement of individual armor plates during repair without the complete removal of the armor of the cylindrical or end surfaces.

The mill drum armor wear rate (g_δ) is determined by the formula (1):

$$g_\delta=\frac{\partial G_\delta}{\partial \tau}, \qquad (1)$$

the ball wear rate (g_b) is determined similarly

$$g_b = \frac{\partial G_b}{\partial \tau}. \quad (2)$$

In [18, 19], analytical dependencies of changes in the values of g_δ and g_b were obtained, according to which it was found that the given dependencies are linear, that is,

$$\frac{g_\delta}{g_b} = \frac{\frac{\partial G_\delta}{\partial \tau}}{\frac{\partial G_b}{\partial \tau}} = \frac{\partial G_\delta}{\partial \tau} \cdot \frac{\partial \tau}{\partial G_b} = M_p, \quad (3)$$

where M_p is the coefficient of proportionality between the wear rate of the drum armor and balls.

It was found that for the drum ball mills KBM 370/850 (Sh-50A), M_p depends on the manufacturer armor characteristics, as well as coal grade.

The relationship between the wear rate of the drum armor and wear rate of grinding balls is linear and is determined by the formula (4):

$$g_\delta = M_p \cdot g_b. \quad (4)$$

The analysis of the studies showed that the ratio of the armor wear rate to the ball wear rate is a constant value. The value of the M_p coefficient for the mill KBM 370/850 (Sh-50A), equipped with armor plates is given in Table 1.

Table 1

Characteristics of the mill metal wear rate depending on coal grade

Parameter		Coal grade [20] ASh	Coal grade [20] GSSh
Metal wear rate, kg/h	balls $\frac{\partial G_b}{\partial \tau}$	31.0	15.1
	drum armor $\frac{\partial G_\delta}{\partial \tau}$	2.15	1.1
Coefficient of proportionality M_p		0.060	0.067

The calculation was performed according to the experimental data taken from Table 1 (for ASh $\frac{\partial G_\delta}{\partial \tau} \Big/ \frac{\partial G_b}{\partial \tau} = 2.15/31 = 0.07$ and for GSSh $\frac{\partial G_\delta}{\partial \tau} \Big/ \frac{\partial G_b}{\partial \tau} = 1.1/15.1 = 0.07$). According to experimental studies, the ratio of the armor wear rate of the drum, equipped with a sleeper armor, to the wear rate of grinding balls is a constant value of 0.07. The M_p coefficient for the mill with a sleeve armor has a value of 0.060 (Table 1).

The ball wear rate was calculated by the formula (5):

$$g_b = g_{b1} \cdot \frac{a_{norm}}{a_{norm1}}, \quad (5)$$

where g_{b1} is the known wear rate of balls in case of GSSh grade coal grinding (Table 1); a_{norm}, a_{norm1} are standard specific expenditures of balls in case of G and GSSh grade coal grinding [4].

The actual armor life depends on the quality of manufacture. According to the place of manufacture in Ukraine, the armor used in mills is divided, as noted earlier, into Bilozersk, Donetsk and Dnipro.

It is known that the armor life is characterized by the actual duration of the maximum interrepair time of the mill. The durations of the maximum interrepair time of the TPP mills, depending on the place of armor manufacture, are given in Table 2.

The duration of the maximum interrepair time of the mill st. No. 8B, the drum of which is equipped with armor plates of Donetsk production is taken as the main parameter for estimating the armor wear rate. According to Table 2, correction factors for the armor wear rate for mills with the Bilozersk or Dnipro armor are determined:

a) Bilozersk armor:
– correction factor $M_1 = 0.8$;
– armor wear rate $g_\delta = 0.05 \cdot g_b$;

b) Dnipro armor:
– correction factor $M_1 = 1.6$;
– armor wear rate $g_\delta = 0.1 \cdot g_b$.

Table 2

The statistics of the interrepair time of Burshtyn TPP mills depending on the armor grade

Place of armor manufacture	Mill st. No.	Interrepair time of the mill: Duration τ, h	Interrepair time of the mill: Average duration τ, h
Donetsk	8B	25194	25194
Bilozersk	9A 10A	34823 27507	31165
Dnipro	1A 1B 3B 5A 6B 12A 12B	14175 17160 13761 16318 8046 18318 19200	15283

Metal loss from the drum armor wear for the interrepair time of the mill was calculated by the formula (6):

$$\Delta G_\delta = \frac{\partial G_\delta}{\partial \tau} \cdot \Delta\tau, \quad (6)$$

where $\Delta\tau$ is the duration of the interrepair time, h.

The drum armor wear magnitude (b_δ) was calculated by the formula (7):

$$b_\delta = \frac{\Delta G_\delta}{G_\delta^n}, \quad (7)$$

where G_δ^n is the initial weight of the drum armor, t.

The over-expenditure of balls during the interrepair time of the mill was calculated by the formula (8):

$$\Delta G_b = \left(\frac{\partial G_\delta}{\partial \tau} \cdot \Delta\tau\right) \cdot M_p = M_p \cdot \Delta G_\delta, \quad (8)$$

where M_p is the coefficient of the armor metal loss recalculation to equivalent over-expenditure of balls in terms of energy costs; for the mill KBM 370/850 (Sh-50A), the coefficient $M_p = 0.36$.

The drum overcharge with balls for the interrepair time of the mill was calculated by the formula (9):

$$G_b^{over} = G_b^{\max} + M_p \cdot \Delta G_\delta, \qquad (9)$$

where $G_b^{\max}$ is the operating maximum charge of the mill according to the parameter chart, t.

The estimated maximum ball charge of the mill, which takes into account the additional weight of balls, replacing the metal weight from the drum armor wear, was calculated by the formula (10):

$$G_b^{over} = G_b^{\max} - M_p \cdot \Delta G_\delta. \qquad (10)$$

According to the method for analytical calculation of the drum armor wear of the mill KBM 370/850 (Sh-50A), the following initial data are required:

– the type of armor coating of the drum (armor plates or sleeper armor) and the place of armor manufacture;

– the grade of coal ground by a mill;

– the value of the duration of the maximum interrepair time of the mill.

Calculation of the armor wear rate of the mill st. No. 8B, the drum of which is equipped with armor plates of Donetsk manufacture, was conducted according to the developed methodology and the initial data.

During the interrepair time, the operating conditions of the mill varied in the following range:

– coal characteristics:

Q_i^w=17.09–20.18 MJ/kg (4081–4819 kcal/kg),

W^P=9.4–12.5 %,

A^P=25.4–35.2 %,

V^G=38.4–40.3 %;

– ball charge of the drum G_b=53–63 t;

– hardness of balls 534 HB.

The initial data for the calculation were:

– a mill with armored plates of Donetsk manufacture;

– «G» grade coal;

– duration of the maximum interrepair time of the mill τ=25194 h.

The results of the calculation of the drum armor wear rates of the mill st. No. 8B of Burshtyn TPP are shown in Table 3.

According to the results of the calculation, the state of armor at the end of the interrepair time of the mill was characterized by:

– the drum armor wear magnitude b_δ=0.5 and the maximum possible metal loss from the drum armor wear ΔG_δ=22.17 t;

– the drum armor wear rate g_δ=0.88 kg/h;

– uncontrolled over-expenditure of balls in the drum ΔG_b=8 t and drum overcharge with balls G_b^{over} =78 t.

The dependencies of the drum armor metal loss ΔG_δ and over-expenditure of balls ΔG_b on the operation duration τ of the mill st. No. 8B are shown in Fig. 1.

The values of the armor wear rate g_δ for the mills whose drums are equipped with the Bilozersk and Dnipro armor are 0.69 and 1.37 kg/h, respectively.

The relationship between the drum armor metal loss ΔG_δ and the time τ is:

$$\Delta G_\delta = 0.89 \cdot \tau, \qquad (11)$$

and the over-expenditure of balls will be determined by the formula (12):

$$\Delta G_b = 0.32 \cdot \tau. \qquad (12)$$

Table 3

Initial data and results of the calculation of the drum armor wear rates of the mill st. No. 8B of Burshtyn TPP

Parameter		Calculation	Calculation result
Initial data			
Initial armor weight G_δ^n, t		–	44
Operating maximum ball charge $G_b^{\max}$, t		–	70
Ball wear rate in case of GSSh coal grinding g_{b1}, kg/h		–	15.7
Standard specific expenditure of balls in case of *G* coal grinding	G a_{norm}, g/t GSSh a_{norm1}, g/t	–	224
Coefficient of proportionality M_p		–	0.067
Conversion factor M_p		–	0.36
Duration of the maximum interrepair time τ, h		–	25194
Calculation of drum armor wear rates			
Ball wear rate g_b, kg/h		$15.7 \cdot \frac{196}{224}$	13.7
Armor wear rate g_δ, kg/h		0.064·13.7	0.88
Metal loss from drum armor wear ΔG_δ, t		0.88·25.194	22.17
Drum armor wear magnitude b_δ		$\frac{22.17}{44}$	0.50
Over-expenditure of balls ΔG_b, t		0.36·22.17	8
Drum overcharge with balls G_b^{over}, t		70+8	78
Estimated maximum ball charge G_b^p, t		70–8	62

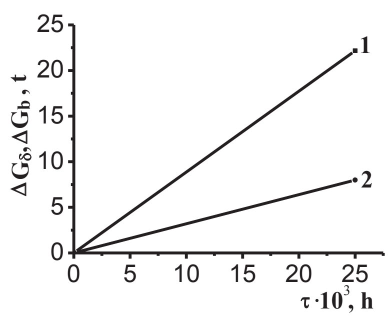

Fig. 1. The dependency of the drum armor metal loss and over-expenditure of balls on the operation duration of the mill st. No. 8B: 1 — drum armor metal loss; 2 — over-expenditure of balls

Fig. 2 shows the dependency of the estimated maximum drum ball charge on the mill operation duration and the place of armor manufacture provided the maximum allowable drum armor wear (b_δ=0.5) and the same estimated maximum ball charge.

Thus, for the timely prevention of uncontrolled increase in the weight of balls in the drum, it is necessary to appropriately take into account the actual drum armor wear when determining the mill ball charge.

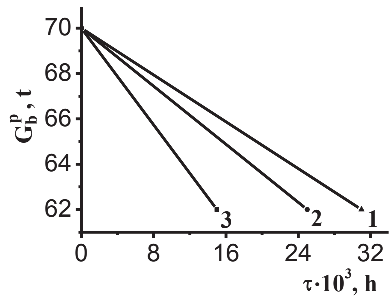

Fig. 2. The dependency of the estimated maximum drum ball charge on the mill operation duration and the place of armor manufacture: 1 – Bilozersk; 2 – Donetsk; 3 – Dnipro

According to Fig. 2, the analytical dependency of the change in the maximum mill drum charge on the operation duration has the form

$$G_b^p = A - B\cdot\tau, \tag{13}$$

where A is the dimensionless coefficient, characterizing the initial optimum charge of the mill; B is the weight coefficient, t/h; τ is the mill operation time, h.

For the mill KBM 370/850 (Sh-50A) with the armor of the Bilozersky manufacturer:

$$G_b^p = 70 - 0.26\cdot\tau, \tag{14}$$

for the armor of the Donetsk manufacturer

$$G_b^p = 70 - 0.32\cdot\tau, \tag{15}$$

for the armor of the Dnipro manufacturer

$$G_b^p = 70 - 0.53\cdot\tau. \tag{16}$$

The obtained analytical dependencies (14)–(16) allow carrying out diagnostics of drum ball mills and planning repair works with the greatest efficiency.

6. Discussion of the results of determining the ball charge, taking into account the mill drum armor wear

Under operating conditions, ball charge is determined by the characteristic $N_m=f(G_b)$ depending on the mill electric motor loading in the case of discharge of the coal material from the drum. During the interrepair time, the constant loading N_m, which, according to the characteristic, corresponds to the operating maximum ball charge $G_b^{\max}$, is maintained by the periodic addition of the required number of new balls in the drum. At the same time, the weight of the metal lost from the armor wear is replaced with the additional weight of balls ΔG_b equivalent in terms of energy costs, which increases the actual total weight of the ball charge to $G_b^{\max} + \Delta G_b + G_b$. Thus, for the drum to have the weight of balls equal to $G_b^{\max}$, it is necessary to maintain the value of the loading N_m, which according to the characteristic corresponds to the value of the estimated maximum ball charge $G_b^p = G_b^{\max} - \Delta G_b$.

According to the calculation results (Table 3), the dependency of over-expenditure of balls on the mill operation duration and the place of armor manufacture was constructed (Fig. 3).

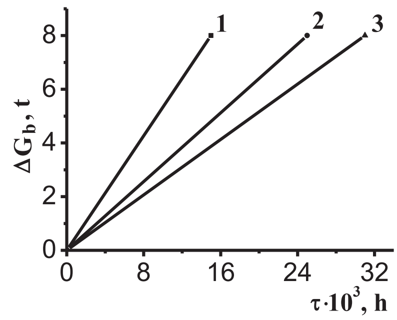

Fig. 3. The dependency of over-expenditure of balls on the mill operation duration and the place of armor manufacture: 1 – Dnipro; 2 – Donetsk; 3 – Bilozersk

According to Fig. 3, the analytical dependency of over-expenditure of balls on the mill operation duration has the form

$$\Delta G_b = B\cdot\tau, \tag{17}$$

where B is the weight coefficient, t/h; τ is the mill operation duration, h.

For the KBM 370/850 (Sh-50A) mill with the armor of the Dnipro manufacturer, the analytical dependency will be:

$$\Delta G_b = 0.53\cdot\tau, \tag{18}$$

for the mill with the armor of the Donetsk manufacturer

$$\Delta G_b = 0.32\cdot\tau, \tag{19}$$

for the mill with the armor of the Bilozersk manufacturer

$$\Delta G_b = 0.26\cdot\tau. \tag{20}$$

Based on the estimated ball charge $G_b^p = 65$ t, the mill electric motor loading $N_m = 950$ kW, whereby the drum would have the actual operating maximum ball charge $G_b^{\max} = 70$ t (Fig. 4) was determined using the formula (21):

$$N_m = 14\cdot G_b + 40, \tag{21}$$

where N_m is the electric motor loading; G_b is the ball charge.

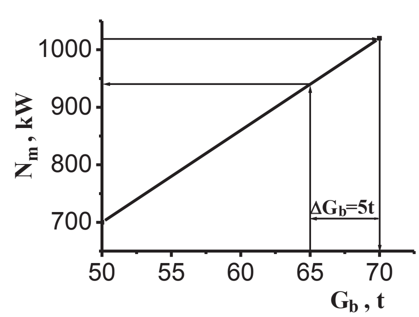

Fig. 4. Determination of the electric motor loading of the mill st. No. 8B in case of the actual ball weight of $G_b^{\max} = 70$ t in the drum

According to the Operating instructions, the adjustment of ΔG_b to the characteristic $N_m=f(G_b)$ is recommended to be introduced periodically – every 4000–5000 hours of mill operation after the beginning of the interrepair time or the construction of a new characteristic. Note that there is no need for the adjustments of ΔG_b to the characteristics after each regular sorting of balls, which, according to the Operating instructions, are carried out with a frequency of at least 2500–3000 hours of mill operation.

7. Conclusions

1. The method of determining the armor wear of the mills KBM 370/850 (Sh-50A) is developed on the example of «G» grade coal grinding, which allows carrying out a partial replacement of armor plates during repair without a complete restoration of armor coating of the cylindrical or end surfaces of the drum.

2. The comparative analysis of armored plates of the mill ball drum is designed and conducted and the main estimation indicator is obtained – the drum armor wear rate depending on the manufacture quality of plates, which is: Bilozersk armor 0.69 kg/h, Donetsk armor 0.88 kg/h; Dnipro armor 1.37 kg/h.

3. The mill ball charge and the mill electric motor loading N_m according to the characteristic $N_m=f(G_b)$ as a function of ball charge G_b are determined.

The developed method allows determining the mill drum armor wear magnitude, and, accordingly, and the mill overcharge with grinding balls, which allows increasing ultimately the reliability and efficiency of the drum ball mill.

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