UDC 621.926.2.004.15

Effective Capacity and Power Efficiency of Designed Machine

V. P. Shtepa[1], A. V. Solovy[1], M. M. Kozerema[1], N. G. Malich[2]

[1] Prydniprovsk State Academy of Civil Engineering and Architecture
24a Chernyshevskogo St., Dnipropetrovsk, 49600, Ukraine
[2] National Metallurgical Academy of Ukraine
4 Gagarin Ave., Dnipropetrovsk, 49600, Ukraine

Analysis of physic-mathematical model recommended on the basis of objective laws of nature led to working out of research technique of power efficiency of current machines. Further theoretical development contributed to creation of method of efficiency parameters definition on the design stage. Synthesis of ideas confirms reliability of analytical dependences as a component of theory related to energy saving in machine production. An example accomplished by data from performance of various foreign breaking machines ("Krupp", Germany) by means of software Math CAD-11 confirms this.

Keywords: POWER EFFICIENCY, POWER SAVING, MACHINE, SOFTWARE

Results and Discussion

Investigation of operating machine on power efficiency or technological process of machine production is possible with the use of physic-mathematical model [1, 2, 5] that determines a functional relation between power and productivity $N = f(P)$. Power balance of machines is put in the basis of this functional relation:

$$N = N_i + \varepsilon_A P + aP^2 \qquad \text{(Eq. 1)}$$

where N - total power consisting of cost items; N_i - power of idle pass; ε_A - specific useful yield used by the machine; P - technical productivity; $\varepsilon_A P$ - power of useful resistance forces; a - factor of supplementary losses caused by useful load; aP^2 - power used for overhead costs (sound, heat, elastic deformation, friction , etc.).

Analysis of equation (1) shows the following: this regression equation which approximates empirical data N and P is a complete square parabola with absolute term N_x - equation grouped from elements of n-order polynomial. And as each term of equation (1) is given a physical substantiation, this relation can be defined as physic-mathematical model.

According to the standard definition of efficiency factor η we will establish a functional ratio $\eta = f(P)$.

$$\eta = \frac{\varepsilon_A P}{Nx + \varepsilon_A P + aP^2} \qquad \text{(Eq. 2)}$$

Graphs $N = f(P)$ and $\eta = f(P)$ in Cartesian coordinate system are introduced in **Figure 1**.

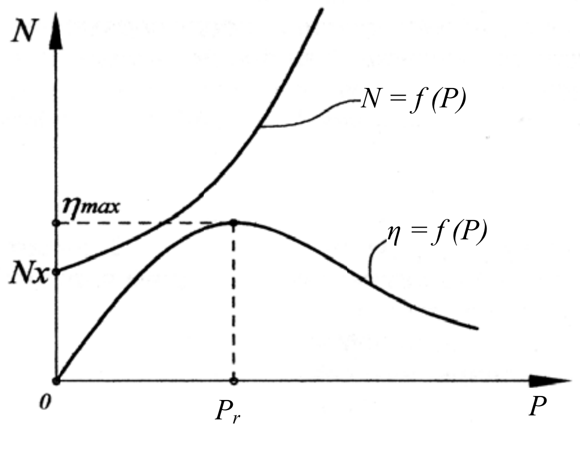

Figure 1. Dependence diagram between efficiency factor of machine and productivity

Parameters of model (1) N_x, N, P are defined experimentally, and efficiency parameters ε_A and a - by means of least-squares method [2].

If establish experimentally only N and P, obtained curve $N = f(P)$ will cross the axis of ordinates in the point of idle pass. And this point will be a numerical value of N_x. In this case, a sufficient number of experiments carried out very extensively in the field of light load is required.

Having investigated function (2) on extremum $\frac{d\eta}{dP} = 0$, we have:

$$\eta_{max} = \frac{1}{1 + \frac{2Nx}{\varepsilon_A P_r}} \qquad \text{(Eq. 3)}$$

$$P_r = \sqrt{\frac{Nx}{a}} \qquad \text{(Eq. 4)}$$

where P_r - rational productivity corresponding to the maximum efficiency (η_{max}), i.e. minimum possible losses in the machine.

The power corresponding to rational loading is expressed by formula

$$N_{Pr} = \varepsilon_A P + 2Nx \qquad \text{(Eq. 5)}$$

It is desirable to define the idle power of the machine at the design stage. It is possible with the use of dynamic force analysis. Theory of Machines and Mechanisms provides this option. However, this is a difficult task because labor-consuming calculations based on construction of diagrams of component forces, speeds and accelerations taking into account friction coefficient, lubrication of rubbing details, weather impact, etc. are required. All these cause a certain error and inaccuracy.

The process of forecasting N_x can be simplified with the use of data of standard series which the designed machine with productivity P refers to.

In this case, we offer the following dependence:

$$Nx_i = AP_i - BP_i^2 + CP_i^3 \qquad \text{(Eq. 6)}$$

where A, B, C – correlation factors, which numerical values are defined from a set of normal equations according to least-squares method:

$$\begin{cases} A\sum_1^n P_i^2 - B\sum_1^n P_i^3 + C\sum_1^n P_i^4 = \sum_1^n Nx_i P_i \\ A\sum_1^n P_i^3 - B\sum_1^n P_i^4 + C\sum_1^n P_i^5 = \sum_1^n Nx_i P_i^2 \\ A\sum_1^n P_i^4 - B\sum_1^n P_i^5 + C\sum_1^n P_i^6 = \sum_1^n Nx_i P_i^3 \end{cases} \qquad \text{(Eq. 7)}$$

where n - number of machines in the standard series; i - serial number of the machine.

Idle power of specified machine (with productivity P_i) is defined by interrelation (6) or graph for given standard series (see example).

Efficiency of designed machine, in particular crushing machine, can be defined by expressions (2, 3, 4) taking into account specific useful work values [4]

$$\varepsilon_A = i\left(\left(\frac{10^{-3}\sigma^2}{4E\gamma} + \frac{cK}{(P + Pc)Km} \right) \right) \qquad \text{(Eq. 8)}$$

where i - reduction ratio equal to the ratio between the greatest size (diameter, D_{max}) of rock subjected to crushing (D_{max}=0.85B; B - width of jaw breaker inlet) to the width of outlet slot, e; σ - ultimate compressive strength of rock, MPa; E - elastic modulus, MPa; γ - rock density, kg/m^3; c - factor depending on design features of crusher and strength of processed material (**Table 1**); K - ratio of length to width of crusher head; P_c=5.6 kg/s - productivity corresponding to displacement of asymptotes of hyperbola (8); K_m=1.5 - nominal factor of crushing mouth.

Rational productivity P_r should be accepted as 0.5P for jaw crushers with compound motion of jaw and 0.7P - for those with simple motion of jaw [3].

So, power corresponding to the rational productivity (P_r) and maximum efficiency (η max) includes the following terms: on overcoming of useful resistance forces ($\varepsilon_A P$) and

Table 1. Value of coefficient *c*

Crushers	σ, MPa				
	30	135	170	210	250
1. With simple motion of crusher jaw (JMS)	0.146	0.658	0.829	1.02	1.22
2. JMS with additional vibration	0.816	3.67	4.62	5.71	6.8
3. With compound motion of crusher jaw (JMC)	0.286	1.29	1.62	2.10	2.38
4. JMC with additional vibration	1.05	4.71	5.93	7.33	8.73
5. JMS with dwell mechanism	1.13	5.09	6.41	7.92	9.43
6. The same with additional vibration	1.28	5.75	7.24	8.94	10.6
7. JMS with vibration drive instead of eccentric one	2.39	10.7	13.5	16.7	19.9

power used for accompanying losses equal to two idle powers ($2N_x$). Functional dependence $Nx_i=f(P_1)$ in one standard series obeys the equation: $Nx_i = AP_i - BP_i^2 + CP_i^3$.

<u>Example of using suggested interrelations with the use of software Math CAD-11</u>

As applied to German crushers manufactured by "Krupp", parameters of power efficiency are computed from formulas (3, 4, 6, 7, 8) taking into account initial data for a standard series consisting of 12 machines:

$$\gamma:=0.003 \quad \zeta:=0.9 \quad K_{engine}:=0.7$$

$$\sigma:=210 \quad E:=6.5\cdot 10^4 \quad c:=1.02$$

$$K_{mouth}:=1.39 \quad K_n:=1 \quad K:=1.6$$

$$P_c:=5.6 \quad i:=0...11 \quad n:=11$$

L: = (315 400 500 630 630 800 800 1000 1000 1250 1500 1700)

B: = (180 224 280 355 450 450 630 630 800 900 1200 1250)

Ny: = (13.4 18.6 29.8 44.7 44.7 59.6 59.6 89.4 96.9 149.1 186.4 201.3)

e: = (37.5 45 52.5 67.5 80 80 127.5 100 160 180 210 230)

P: = (5.417 9.583 16.25 33.333 39.583 52.083 62.5 81.25 106.25 175 250 312.5)

We define reduction ratio of material, outlet slot area and nominal relation of length to width of crusher chamber, respectively (**Table 2**):

$$I_{o,i} := \frac{(0.85 \cdot B_{o,i})}{e_{o,i}}$$

$$K_{m_{o,i}} := \frac{L_{o,i}}{B_{o,i}}$$

$$F_{slot_{o,i}} := \frac{L_{o,i} e_{o,i}}{100}$$

Table 2. Reduction ratio of material, outlet slot area , nominal relation of length to width of crusher chamber

$I_{o,i}$	$Fslot_{o,i}$	$Km_{o,i}$	εAi	N_{xli}	η_{max}	η_i	N_{xi}
4.08	118.125	1.75	0.576	2.282	0.324	0.275	0.977
4.231	180	1.786	0.494	3.027	0.354	0.301	1.711
4.533	262.5	1.786	0.446	4.968	0.338	0.287	2.856
4.47	425.25	1.775	0.358	7.075	0.371	0.316	5.617
4.781	504	1.4	0.394	5.801	0.485	0.412	6.567
4.781	640	1.778	0.346	8.693	0.421	0.358	8.371
4.2	$1.02 \cdot 10^3$	1.27	0.317	8.079	0.462	0.392	9.777
5.355	$1 \cdot 10^3$	1.587	0.366	12.098	0.463	0.393	12.091
4.25	$1.6 \cdot 10^3$	1.25	0.29	13.619	0.442	0.376	14.751
4.25	$2.25 \cdot 10^3$	1389	0.268	21.132	0.437	0.372	19.676
4.857	$3.15 \cdot 10^3$	1.25	0.299	20.736	0.558	0.474	21.354
4.62	$3.91 \cdot 10^3$	1.36	0.279	20.214	0.601	0.511	20.097

The factor of relation between length and width of chamber can be presented in the form of one-line matrix:

Km: = (1.75 1.786 1.786 1.775 1.4 1.778 1.27 1.587 1.25 1.389 1.25 1.36)

According to formula (8) we will determine the values of specific useful work as well as idle power of each machine from the standard series (**Table 2**)

$$\varepsilon A_i := I_{o,i}\left[\frac{10^{-3}\cdot\sigma^2}{4E\cdot\gamma}+\frac{c\cdot K}{(P_{o,i}+P_c)\cdot Km_{o,i}}\right]$$

$$Nxl_1 := 0.5\cdot K_d\cdot(\frac{Ny_{o,i}}{K_m\cdot K_n}-\varepsilon A_i\cdot P_{o,i}$$

From formula (3) efficiency of crusher is (**Table 2**):

$$\eta_{max1} := \frac{1}{1+\dfrac{2\cdot Nxl_1}{K_d\cdot\varepsilon A_i\cdot P_{o,i}}}$$

$$\eta_{engine} := 0.85$$

$$\eta_i := \eta_{max1}\cdot\eta_{engine}$$

Using formulas (6) and (7) we will construct a dependence diagram between idle power and productivity of machines (**Figure 2**):

$a := \sum_{i=0}^{11}(P_{0,i})^2$ $\quad b := -\sum_{i=0}^{11}(P_{0,i})^3$ $\quad a1 := \sum_{i=0}^{11}(P_{0,i})^3$ $\quad b1 := -\sum_{i=0}^{11}(P_{0,i})^4$

$a2 := \sum_{i=0}^{11}(P_{0,i})^4$ $\quad b2 := -\sum_{i=0}^{11}(P_{0,i})^5$ $\quad k := \sum_{i=0}^{11} Nxl_1\cdot P_{0,i}$ $\quad c := \sum_{i=0}^{11}(P_{0,i})^4$

$k1 := \sum_{i=0}^{11} Nxl_1\cdot(P_{0,i})^2$ $\quad c1 := \sum_{i=0}^{11}(P_{0,i})^5$ $\quad k2 := \sum_{i=0}^{11} Nxl_1\cdot(P_{0,i})^3$ $\quad c2 := \sum_{i=0}^{11}(P_{0,i})^6$

$$A := \frac{\left|\begin{pmatrix} k & b & c \\ k1 & b1 & c1 \\ k2 & b2 & c2 \end{pmatrix}\right|}{\left|\begin{pmatrix} a & b & c \\ a1 & b1 & c1 \\ a2 & b2 & c2 \end{pmatrix}\right|} \quad B := \frac{\left|\begin{pmatrix} a & k & c \\ a1 & k1 & c1 \\ a2 & k2 & c2 \end{pmatrix}\right|}{\left|\begin{pmatrix} a & b & c \\ a1 & b1 & c1 \\ a2 & b2 & c2 \end{pmatrix}\right|} \quad d := \frac{\left|\begin{pmatrix} a & b & k \\ a1 & b1 & k1 \\ a2 & b2 & k2 \end{pmatrix}\right|}{\left|\begin{pmatrix} a & b & c \\ a1 & b1 & c1 \\ a2 & b2 & c2 \end{pmatrix}\right|}$$

$$Nx_1 := A \cdot P_{0,i} - B \cdot (P_{0,i})^2 + d \cdot (P_{0,i})^3$$

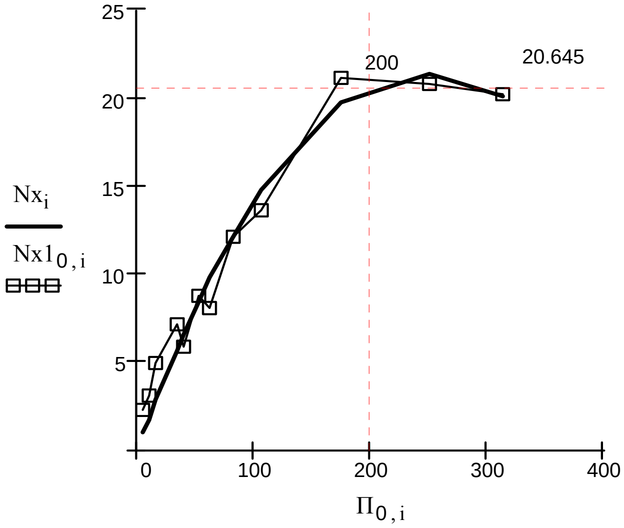

Figure 2. Dependence diagram between idle pass and productivity

Interrelation (and approximating curve) between idle power (Y-axis) as productivity function (X-axis) of the standard series of crushing machines manufactured by "Krupp" is presented in the diagram according to formula (6).

Conclusions

Given example of using interrelations and constructed diagram makes it possible to forecast idle power (N_x) and efficiency (η) of future machine, for example, P= 200, then idle power of given machine (N_x) can be determined from the diagram or expression (6). Thus, N_x=20.645. The maximum efficiency (η_{max}) of the machine can be defined taking into account formulas (4) and (8): $\eta_{max} = 0.494$.

References

1. V. P. Shtepa, V. M. Gene. *Mineral Dressing,* 1978, Issue 22, pp. 29-33.*
2. V. P. Shtepa *Izvestiya Vuzov. Mashinostroenie*, 1991, No. 7-9, pp. 16-20.*
3. V. P. Shtepa *Metallurgicheskaya i Gornorudnaya Promyshlennost*, 1977, No. 1, pp. 81-84.*
4. V. M. Gene, V. P. Shtepa. *Mineral Dressing,* 1983, Issue 33, pp. 71-80.*
5. V. M. Gene, V. P. Shtepa, A. S. Shipilov. *Inventor's Certificate* 1281934 (USSR). *

* Published in Russian

Received March 25, 2010

Прогнозирование полезной работы и КПД проектируемой машины

Штепа В.П., Соловий А.В.,
Козерема А.В., Малич Н.Г.

Анализ физико-математической модели, предложенный на основе объективных законов природы, привел к разработке методики исследования энергетической эффективности существующих машин. Дальнейшее теоретическое развитие способствовало созданию методики определения показателей эффективности их на стадии проектирования. Синтез идей убедительно подтверждает достоверность предложенных аналитических зависимостей, как составной части теории, направленной на энергосбережение при машинном производстве. Пример, выполненный по данным из технической характеристики типоразмерного ряда зарубежных дробилок [Германия (фирма «Krupp»)], с помощью возможностей программного обеспечения Math CAD-11, в подтверждение тому.