DOI 10.1007/s11148-016-9984-8
Refractories and Industrial Ceramics *Vol. 57, No. 4, November, 2016*

HEAT ENGINEERING

MONITORING OF PROCESS FLOW DIAGRAMS IN THE PRODUCTION OF FERROUS METALS

S. Sh. Kazhikenova[1,2]

Translated from *Novye Ogneupory*, No. 7, pp. 33 – 35, July, 2016.

Original article submitted March 3, 2016.

Any improvement in the technological processes involved in the production of ferrous and nonferrous metals, taking into account the existence of lean crude metal and of crude metal that is heterogeneous in terms of composition, should be done not only on the basis of the traditional methods that are used to reveal cause-effect relations in the processes present in the common process flow diagram accompanied by an analysis of their material and heat balances. An additional analysis of these processes is possible on the basis of Shannon information entropy in order to combine as yet uncoordinated indicators on the basis of the content and degree of recovery of valuable components in technological products on the process flow stages and, on the whole, throughout the entire process flow diagram. This is done for the purpose of conducting a comparative analysis and evaluation of the metallurgical processes. Information criteria for an exhaustive evaluation of the uncertainty and degree of completeness of the process flow diagrams of steel production are developed on the basis of an entropy information analysis of the process flow diagrams of ferrous metallurgy.

Keywords: entropy, information, metallurgical process, steel production, entropy information analysis, recovery

In view of the existence of lean crude metal and of crude metal that is heterogeneous in terms of composition, any improvement in the processes involved in the production of ferrous metals is possible only on the basis of an analysis of their material and heat balances. An additional analysis that takes into account the entropy information aspects in order to determine the balance between uncertainty and the degree of completeness of the technological process stages or of the process flow diagram as a whole is also needed. Such an extension is dictated by the fact that, whereas the material and heat balances are based on the use of universal laws of conservation of mass and energy, the last of the universal laws of conservation, i.e., the law of conservation of the sum of information and entropy, has still not been applied in the field of metallurgy.

Shannon's statistical formula

$$H = -\sum_{i=1}^{N} p_i \log_2 p_i,$$

is widely used for purposes of entropy information analysis of arbitrary objects [1]. Here H is the entropy characteristic and p_i the probability of discovering elements in their set N with

$$N; \sum_{i=1}^{N} p_i = 1, \ p_i \geq 0.$$

Prior to publication of the theory created by Shannon, R. Hartley had suggested that the quantity of information could be determined by the formula [2]

$$H_{n(\max)} = k^n \log N_0, \qquad (1)$$

where n is the ordinal number of the level of a system, $n \in Z$, $n \geq 0$; k, length of code of elements on each level; and N_0, number of elements on level $n = 0$.

---

[1] Buketov Karaganda State University, Karaganda, Republic of Kazakhstan.
[2] sauleshka555@mail.ru

Let us consider a process flow diagram with $k = 2$. We will graphically illustrate the difference between the differential and integral models (Table 1) in terms of the coordinates n and d on the basis of Fig. 1.

We adopt the content of the principal element of a system, expressed as a fraction, as a characteristic of the probability of discovering this element. For example, this may be the content of a recovered chemical element (e.g., iron) in corresponding products. The same may be said for the process of recovering an element in some product in general. Then, applied to a unique controlled element of the system, the usual mathematical calculations for the expression of the information uncertainty become more compact and reduce to the following. If p is the probability of discovering a controlled element in a product or a technological process in the course of recovery, the uncertainty of the behavior of only a single element of the system is expressed by the formula

$$H = \log_2 \frac{1}{p} = -\log_2 p = -\frac{\ln p}{\ln 2}. \qquad (2)$$

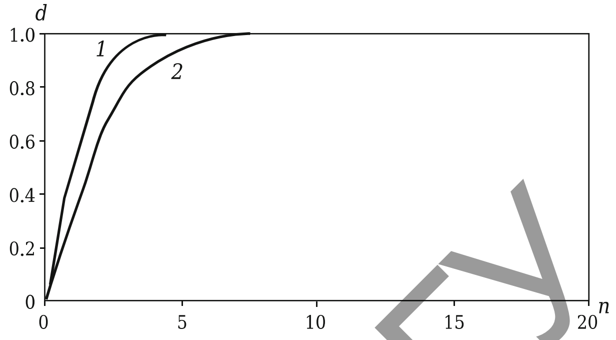

Fig. 1. Degree of determination d as a function of the level n of an ideal hierarchical system: *1*) differential model; *2*) integral model.

We define the quality of the technological process stages and the processed products on the basis of a comparative analysis of competing flow diagrams from a common generalized criterion of complex uncertainty and degree of completeness of the process flow diagram for the production of steel in blast furnaces and direct acquisition of iron. Since the

TABLE 1. Computed Entropy Information Characteristics of Technological Process Stages in a Hierarachical System for k = 2, N_0 = 2

n	$I_n(d)$, bit/element*	$H_{n(\max)}$, bit/element	$d_n = \frac{I_n(d)}{H_{n(\max)}}$	$I_{\Sigma n}(d)$, bit/element	$H_{\Sigma n(\max)}$, bit/element	$d_{\Sigma n} = \frac{I_{\Sigma n}(d)}{H_{\Sigma n(\max)}}$
	$2^n\left[1-\frac{1}{(n+1)!}\right]$	2^n	$\left[1-\frac{1}{(n+1)!}\right]$	$\sum_{i=0}^{n} 2^i\left[1-\frac{1}{(i+1)!}\right]$	$\sum_{i=0}^{n} 2^i$	$\frac{\sum_{i=0}^{n} 2^i\left[1-\frac{1}{(i+1)!}\right]}{\sum_{i=0}^{n} 2^i}$
0	0	1.0	0	0	1.0	0
1	1.0000	2.0	0.5000	1.0000	3.0	0.3333
2	3.3333	4.0	0.8333	4.3333	7.0	0.6190
3	7.6667	8.0	0.9583	12.0000	15.0	0.8000
4	15.8667	16.0	0.9917	27.8667	31.0	0.8989
5	31.9556	32.0	0.9986	59.8222	63.0	0.9496
6	63.9873	64.0	0.9998	123.8095	127.0	0.9749
7	127.9968	128.0	1.0	251.8063	255.0	0.9875
8	255.9993	256.0	1.0	507.8056	511.0	0.9937
9	511.9999	512.0	1.0	1019.8055	1023.0	0.9969
10	1024.0000	1024.0	1.0	2043.8055	2047.0	0.9984
11	2048.0000	2048.0	1.0	4091.8055	4095.0	0.9992
12	4096.0000	4096.0	1.0	8187.8055	8191.0	0.9996
13	8192.0000	8192.0	1.0	16379.8055	16383.0	0.9998
14	16384.0000	16384.0	1.0	32763.8055	32767.0	0.9999
15	32768.0000	32768.0	1.0	65531.8055	65535.0	1.0
16	65536.0000	65536.0	1.0	131067.8055	131071.0	1.0

* $I_n(d)$ — information characteristic (information) of system on m-th level of hierarchical system; bit/element — unit of measurement of the quantity of information and entropy (dimension of bit per element)

TABLE 2. Information Evaluation of Steel Production in Blast Furnaces

Technological Process Stage	Content Indicators α		Content Indicators β		$H_{\alpha\beta}$	$p_{\alpha\beta}$
	α	H_α, bit	β	H_β, bit		
Mining	0.5000	1.0000	0.1020	3.2934	4.2934	0.0510
Concentration	0.6550	0.6104	0.8700	0.2009	0.8113	0.5696
Furnace Melting	0.8830	0.1795	0.9910	0.0130	0.1925	0.8751
Melting	0.9550	0.0664	0.9980	0.0029	0.0693	0.9531
Remelting	0.9950	0.0072	0.9990	0.0014	0.0086	0.9940
Refining	0.9999	0.0001	0.9999	0.0001	0.0002	0.9998
H_k, bit	—	1.8636	—	3.5117	5.3753	—
p_k, fractions	0.2748	—	0.0877	—	—	2.4087×10^{-2}

TABLE 3. Information Evaluation of Steel Production by Direct Acquisition of Iron

Technological Process Stage	Content Indicators α		Content Indicators β		$H_{\alpha\beta}$	$p_{\alpha\beta}$
	α	H_α, bit	β	H_β, bit		
Mining	0.5000	1.0000	0.1020	3.2934	4.2934	0.0510
Concentration	0.7140	0.4860	0.8920	0.1649	0.6509	0.6368
Metallization	0.9800	0.0291	0.9950	0.0072	0.0363	0.9751
Melting	0.9910	0.0130	0.9980	0.0029	0.0159	0.9890
Remelting	0.9950	0.0072	0.9990	0.0014	0.0086	0.9940
Refining	0.9999	0.0001	0.9999	0.0001	0.0002	0.9998
H_k, bit	—	1.5354	—	3.4699	5.0053	—
p_k, fractions	0.3449	—	0.0902	—	—	3.1131×10^{-2}

recovery of any component is proportional to its content in the initial substance and inversely proportional to the content in the product, recovery of iron from the Earth's crust in a mineral deposit may be estimated by the expression

$$\beta_0 \cong \frac{\alpha_E}{\alpha_D}, \qquad (3)$$

where the indicator β_0 expresses the rate of recovery on the zeroth level of the process flow diagram; α_E, an indicator that expresses the content in the Earth's crust; and α_D, an indicator that expresses the percentage content in the mineral deposit.

Since for iron $\alpha_E = 5.1\%$ [3] and $\alpha_D \cong 50.0\%$, we have

$$\beta_0 \cong \frac{\alpha_E}{\alpha_D} \cdot 100\% = \frac{5.1}{50.0} \cdot 100\% = 10.2\%. \qquad (4)$$

Using Shannon's information formula (2), we carry out an entropy information analysis of each technological process stage and the process flow diagram as a whole using the production of steel as an example. Once the characteristic of the complex uncertainty of the process flow diagram H_k has been found, we are able to find, by means of the inverse formula [4]

$$p_k = \exp(-H_k \ln 2) = 2^{-H_k}\text{, fractions,} \qquad (5)$$

the characteristic of the complex uncertainty of the process flow diagram for the production of steel corresponding to it.

An equivalent correlation ($R = 0.847942$, $t_R = 6.035314 > 2$ for a systems determination, $R = 0.991408$, $t_R = 115.8812 > 2$ for a level determination) is established by comparing reference data on the recovery and content of a valuable component on the basis of the technology of steel production in blast furnaces (Table 2) with the characteristics of the new model (2) and (5). An equivalent correlation ($R = 0.733544$, $t_R = 3.176112 > 2$ for a systems determination, $R = 0.96213$, $t_R = 25.89641 > 2$ for a level determination) is also established in the production of steel through direct acquisition of iron (Table 3). A comparison of the computed data using the new model (2) and (5) with operating data is shown in Fig. 2.

Thus, on the basis of an entropy information analysis I was able to determine a closer correlation between the operating results of the production of ferrous meals with a differ-

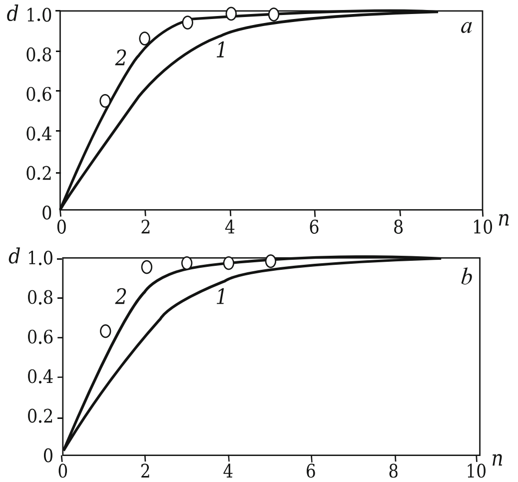

Fig. 2. Information evaluation of indicators as functions of the level *n* of the process flow diagram for steel production in blast furnaces (*a*) and in direct acquisition of iron (*b*): *1*) systems determination; *2*) level determination; the small circles indicate operating data.

ential model of an ideal hierarchical system, attesting to a more detailed development of each process stage in ferrous metallurgy, in contrast to the production of nonferrous metals. A more well-grounded treatment of each process stage in ferrous metallurgy is also attested to by the fact that, in most cases, the intermediate products of the different process stages are realized as independent commercial products between enterprises in the branch on the scale of an individual country as well as on the scale of several countries.

The basic trend in the development of processes involved in the direct reduction of iron from ore is defined today by an expansion of the volume of production of pure sponge iron and high-quality metalized charge as well as by an intensification of the use of iron for steelmaking. But a comparative evaluation based on the entropy information characteristics of the two alternative processes of steelmaking show that today there is still no industrial technology that is comparable in terms of capacity with traditional furnace production or corresponding plants for activation of such a process, as is confirmed by the close proximity of furnace production to an ideal hierarchical system.

In order to improve steel smelting production specialists of many leading metallurgical firms from around the world have continued to develop ecologically safe and less expensive steelmaking technologies. An active search has been underway in recent years in the worldwide steel casting industry for profitable technologies that could replace the traditional process of steel production in blast furnaces and basic oxygen furnaces. But, according to our predictions, the blast furnace process of steel production will nevertheless continue to dominate all other processes used in the production of steel. Such is the result of an information evaluation of the certainty of the implementation of process flow diagrams, a result that may be used to compare their states before and after any improvement together with the base characteristic of the complex uncertainty.

REFERENCES

1. C. E. Shannon, A mathematical theory of communications, *Bell. Systems Tech. J.*, **27**, 623 – 656 (1948).
2. R. Hartley, The transmission of information, in: *Theory of Information and its Applications*, by R. Hartley [Russian translation], IL, Moscow (1959), pp. 5 – 35.
3. N. V. Gudima and Ya. P. Sheyn, *A Brief Handbook on the Metallurgy of Nonferrous Metals* [in Russian], Metallurgiya, Moscow (1975), 536 pp.
4. V. P. Malyshev, S. Sh. Kazhikenova, and A. Turdukozhaeva, A qualitative and quantitative evaluation of the technological processes in the metallurgy of nonferrous metals, *Russian Journal of Non-ferrous Metals*, **50**(4), 335 – 337 (2009).