A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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M. KIELOCH*, Ł. PIECHOWICZ*, J. BORYCA*

CORRELATION BETWEEN HEAT CONSUMPTION AND STEEL LOSS FOR SCALE IN THE TWO-STAGE HEATING PROCESS

WSPÓŁZALEŻNOŚĆ ZUŻYCIA CIEPŁA I STRATY STALI NA ZGORZELINĘ W DWUETAPOWYM PROCESIE NAGRZEWANIA

On the basis of the authors' own investigation and computations a correlation between the consumption of heat and the loss of steel for scale in a two-stage heating process has been established. The results of numerical computation of heat consumption and steel loss for scale, as performed based on the mathematical model for the pusher furnace, are given. The results of both numerical computation and laboratory tests were subjected to mathematical interpretation. It has been found that the dependence of heat consumption on steel loss can be described with simple equations.

Keywords: heat consumption, loss of steel, heating process, heating technology

Na podstawie wyników własnych badań i obliczeń ustalono współzależność zużycia ciepła i straty stali na zgorzelinę w dwuetapowym procesie nagrzewania. Zaprezentowano wyniki obliczeń numerycznych zużycia ciepła i straty stali na podstawie modelu matematycznego pieca przelotowego. Zarówno wyniki obliczeń numerycznych jak i badań laboratoryjnych zostały poddane interpretacji matematycznego. Ustalono, że zależność zużycia ciepła od straty można opisać prostymi równaniami.

List of some more important designations

A, B, C, D, N – constants in the steel oxidation equation,
N_0, P, P_0 – constants,
a – temperature conductivity, m^2/h or m^2/s,
L – furnace heating chamber length, m,
l – length of the charge being heated, m,
M – surface temperature increase rate, K/h or K/s,
s – computational length of the charge being heated, m,
T – temperature, K,
t – temperature, °C,
Δt – temperature difference, K,
z – surface steel loss, kg/m^2,
α – excess air ratio,
ρ – specific mass, kg/m^3,
$\dot{Q}$ – heat flux, kW,
q – unit heat consumption, kJ/kg,
τ – time, s or h,
$\Delta\tau$ – time difference (time step), s or h.

List of some more important designations

p – heating period,
w – soaking period.

1. Introduction

The literature on the subject, barring few exceptions, does not provide any investigation and computation results, nor analytical derivations concerning the correlation between the consumption of heat and the loss of steel for scale. The results of investigations [1, 2] and computations [3, 4, 5] have showed a relationship to exist between the heat consumption and the steel loss.

The increase in steel loss has a corresponding increase in the unit consumption of heat (Fig. 1). The both indices determine the heating costs [6, 7] and their value depends, above all, on the adopted technology, efficiency and heating intensity [8]. All of these factors are dependent on each other and conditioned by the distribution of temperatures on the charge surface, which determines the total heating time.

Thus, low outlays on heating will only be possible in those furnaces, where a small loss of steel for scale could be obtained.

* DEPARTMENT OF INDUSTRIAL FURNACES AND ENVIROMENTAL PROTECTION, TECHNICAL UNIVERSITY OF CZĘSTOCHOWA, 42-200 CZĘSTOCHOWA, AL. ARMII KRAJOWEJ 19, POLAND

The physical modelling of thermal phenomena that occur in industrial furnaces is practically infeasible.

Finding a correlation between the consumption of heat and the loss of steel for scale will allow the computation of heat consumption indices, while using the values of steel loss.

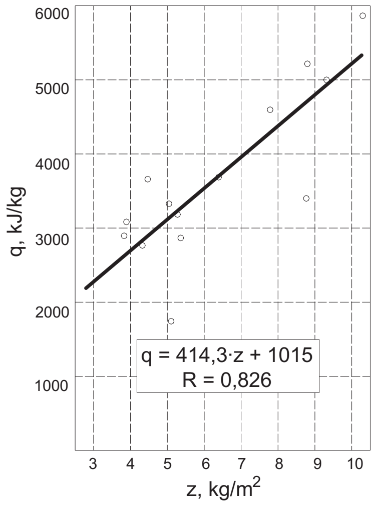

Fig. 1. Dependence of heat consumption on the loss of steel for scale for the pusher furnace

2. Theoretical bases

Fort the purposes of deriving a general form of the dependence of heat consumption on steel loss, the simplest heating process technology consisting of the two following stages was assumed (Fig. 2):

Stage I – carried out with a linear increase in charge surface temperature, and

Stage II – carried out with a constant charge surface temperature.

For this technology, the total heating time, τ_n, will be the sum of the times of the heating and the soaking stages.

The main index determining the steel heating costs is the heat consumption per unit mass of the finished product.

Works [9, 10] have established that, for the adopted technology, the dependence of the value of unit heat consumption on the surface temperature increase can be described by the following equation:

$$q = q_1 + \frac{\left[\sum\limits_{i=1}^{\infty} \dot{Q}_{2i} + \sum\limits_{i=1}^{\infty} f_i\left(M^{n_i}\right)\right] \cdot \left[\left(t''_p - t'_p\right) \cdot P \cdot a_w + M \cdot s^2 \cdot \ln\left(N_0 \cdot \frac{M \cdot s^2}{a_p} \cdot \frac{1}{\Delta t_k}\right)\right]}{2P \cdot a_w \cdot s \cdot l \cdot L \cdot \rho \cdot n \cdot M}. \tag{1}$$

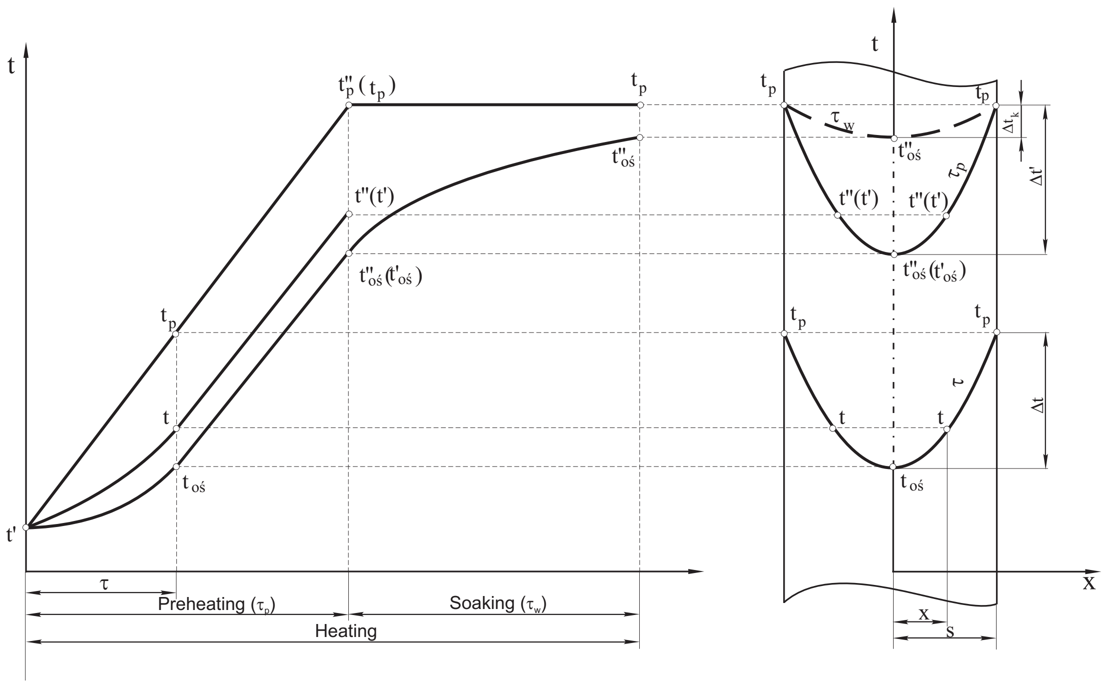

Fig. 2. Two-stage charge heating process

This model can be fully used for qualitative computation and also for carrying out computation to determine the heating technology.

Another essential index determining the heating costs is the loss of steel for scale.

Works [11, 12] have found that the dependence of steel loss on the heating rate can be expressed as follows:

$$z = \left[\frac{A \cdot \alpha_p^C \cdot \int_{T_p'}^{T_p''} \exp\left(-\frac{D}{T}\right) dT}{M} + P_0 \cdot A \cdot \alpha_w^C \cdot \frac{s^2}{a_w} \cdot \exp\left(-\frac{D}{T_w}\right) \cdot \ln\left(N_0 \cdot \frac{M \cdot s^2}{a_p} \cdot \frac{1}{\Delta t_k}\right) \right]^B \tag{2}$$

The developed mathematical model enables both the quantitative and the qualitative computations of steel loss in the two-stage heating process.

Assuming $\sum_{i=1}^{\infty} f_i(M^{n_i}) = 0$ in Equation (1), this relationship can be reduced to the form of:

$$q = \frac{A_1}{M} + B_1 \cdot \ln(C_0 \cdot M) + b. \tag{3}$$

From Equation (2), the following can be obtained:

$$z^N = \frac{A_2}{M} + B_2 \cdot \ln(C_0 \cdot M), \tag{4}$$

where: $N = \frac{1}{B}$.

Equations (3) and (4) indicate a close correlation between heat consumption and the loss of steel for scale.

3. Numerical computation of heat consumption and steel loss

The accurate, quantitative computation of heat consumption can be made using numerical methods [13, 14, 15].

To perform the computer simulation of the effect of heating rate on the consumption of heat, a program for the numerical computation of charge heating and heat exchange in the furnace chamber was devised. The numerical computations of charge heating were performed using the elementary balances method. Blooms or slabs of the thickness of 2s and the length of l make up the charge.

The computation of heat exchange in the furnace chamber was performed using a zone method.

The inner space of the furnace was divided into 20 computational zones, in which isothermal surfaces and isothermal gaseous bodies were separated.

The problem of radiation heat flow was solved by using the brightness and configuration ratios method. In the heat exchange computation, the convection transfer was accounted for.

The heating process was assumed to proceed in two stages with a linear increase in charge surface temperature in the heating-up period. The computations were performed for seven heating rates ranging from 100 to 700 K/h.

For each heating rate, a separate furnace chamber temperature field was established, which was intended to ensure the assumed heating parameters, namely:

- the final value of surface temperature – $t_p'' = 1250°C$, and
- the final temperature difference on the charge cross-section – $\Delta t_k = 50$ K.

For the purposes of computation of the loss of steel for scale it was assumed that, for each heating rate, the heating would be carried out in a model pusher furnace for preset heating parameters. The computations of steel loss were performed using the numerical modelling of charge heating. For the heating-up period, the boundary condition of the 1st type was assumed, in the following form:

$$T_p = T_o + M \cdot \tau \tag{5}$$

To compute the temperature of the arbitrary differential element "i" in the successive time interval, the explicit differential scheme was employed:

$$T_i^{k+1} = T_i^k + \Delta\tau \cdot \frac{a \cdot n^2}{s^2} \cdot \left(T_{i-1}^k + T_{i+1}^k - 2 \cdot T_i^k\right). \tag{6}$$

In Equation (6), the averaged temperature conductivity is used.

For the heating-up period, the loss of steel in the time interval $\Delta\tau$ and at the temperature of T_z was computed according to the equation below:

$$z_{p_i}^N = A \cdot \Delta\tau \cdot \alpha_p^C \cdot \exp\left(-\frac{D}{T_{zi}}\right). \tag{7}$$

For the soaking period, the loss of steel was computed from the following relationship:

$$z_w^N = A \cdot \tau_w \cdot \alpha_w^C \cdot \exp\left(-\frac{D}{T_w}\right). \tag{8}$$

For the entire heating process, the loss of steel was computed according to the following equation:

$$z^N = \sum_i \left(z_{p_i}^N\right) + z_w^N. \qquad (9)$$

The values of the empirical constants A, C, D, N were taken from the data provided in work [16]. Moreover, it was assumed for the computation that:

– $\alpha_p = 1,05$, $a_p = 0,02025$ m^2/h,
– $\alpha_w = 1,05$, $a_w = 0,02067$ m^2/h.

The computational block for the computation of the loss of steel for scale is shown in Fig. 3. The computational procedure was executed in the MathCad® 2000 Professional environment.

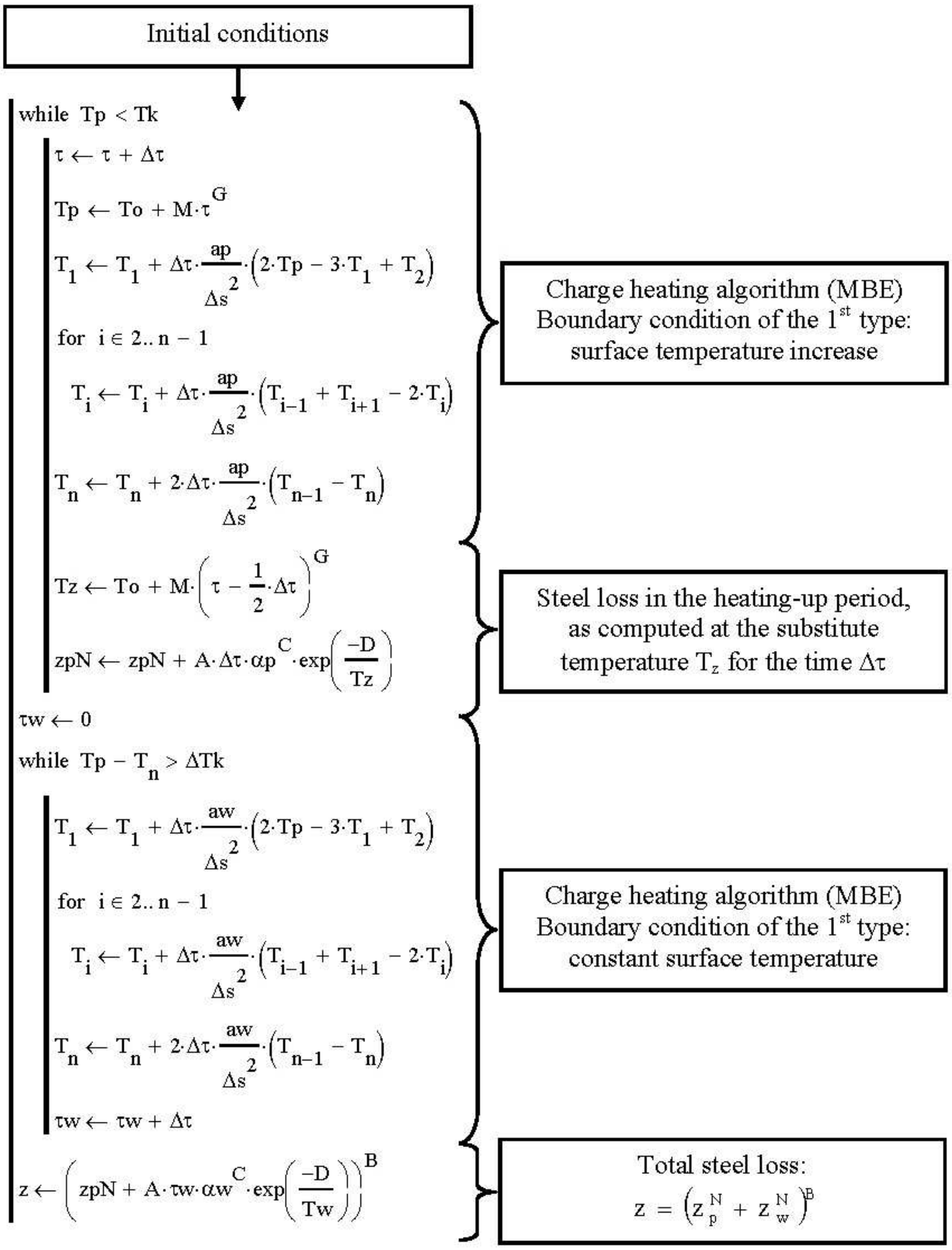

Fig. 3. Procedure for the computation of steel loss

4. Mathematical analysis of numerical computation results

Both the unit heat consumption and the steel loss as a function of heating rate can be adequately described with a few functions written in a general form.

For the purpose of the present study, approximations are used, whose mathematical notation allows a general form of the relationship of heat consumption versus steel loss to be derived. Moreover, the applied functions sufficiently accurately describe the discrete values of numerical computations.

For the mathematical interpretation of the numerical computations of heat consumption and steel loss, approximation functions of the same type were used, as follows:

$$q = A_1 + B_1 \cdot \exp(C_1 \cdot M) \tag{10}$$

$$z = A_2 + B_2 \cdot \exp(C_2 \cdot M). \tag{11}$$

There are approximations that better describe the computed values (Tables 1, 2); however, due to their complex form, they cannot be used for further derivations.

Tables 1 and 2 compare several approximating functions by showing their basic parameters that determine the accuracy of description, i.e.:

- correlation coefficient, R,
- maximum relative description error (maximum difference), $\Delta q_{\max}$, $\Delta z_{\max}$,
- mean relative description error (maximum difference), $\Delta q_{śr}$, $\Delta z_{śr}$.

The relative description error was computed from the following relationship:

$$\Delta q\,(\Delta z) = \left|\frac{q_n\,(z_n) - q_a\,(z_a)}{q_n\,(z_n)}\right| \cdot 100\%, \tag{12}$$

where: $q_n(z_n)$ – numerical computation of heat consumption (steel loss), $q_a(z_a)$ – computation of heat consumption (steel loss) using approximating functions.

The numerical computation results and their mathematical interpretation is presented graphically. Figure 4 represents the effect of heating rate on the unit consumption of heat in the model pusher furnace.

The effect of heating rate on the loss of steel in the model furnace is illustrated in Fig. 5.

TABLE 1

List of approximations $q = f(M)$

Approximations for M = 100 do 700 K/h	A_1	B_1	C_1	D_1	R	$\Delta q_{\max}$, %	$\Delta q_{śr}$, %
$q(M) = A_1 \cdot \exp(B_1 \cdot M) + C_1 \cdot \exp(D_1 \cdot M)$	2223.7629	0.00023	4058.62109	−0.01028	0.99928	1.033	0.538
$q(M) = \frac{A_1}{M} + B_1 \cdot \ln(C_1 \cdot M)$	272826.1346	608.06119	0.05271	–	0.99757	1.820	0.924
$q(M) = A_1 + B_1 \cdot \exp(C_1 \cdot M)$	2540.21137	5133.69872	−0.01461	–	0.99472	3.466	1.199
$q(M) = A_1 + \frac{B_1}{M}$	2241.45671	140497.63883	–	–	0.96493	7.197	3.477

TABLE 2

List of approximations $z = f(M)$

Approximations for M = 100 do 700 K/h	A_2	B_2	C_2	D_2	R	$\Delta z_{\max}$, %	$\Delta z_{śr}$, %
$z(M) = \left[\frac{A_2}{M} + B_2 \cdot \ln(C_2 \cdot M)\right]^{0.75}$	667.11643	1.59234	0.01267	–	0.99999	0.131	0.056
$z(M) = \frac{A_2}{M} + B_2 \cdot \ln(C_2 \cdot M)$	322.88686	0.76486	0.04204	–	0.99997	0.185	0.082
$z(M) = A_2 \cdot \exp(B_2 \cdot M) + C_2 \cdot \exp(D_2 \cdot M)$	2.80308	0.00012	5.79811	−0.01359	0.99995	0.269	0.140
$z(M) = A_2 + B_2 \cdot \exp(C_2 \cdot M)$	2.99288	7.34322	−0.01705	–	0.99791	1.837	0.805
$z(M) = A_2 + \frac{B_2}{M}$	2.64641	156.43456	–	–	0.95877	5.871	3.678

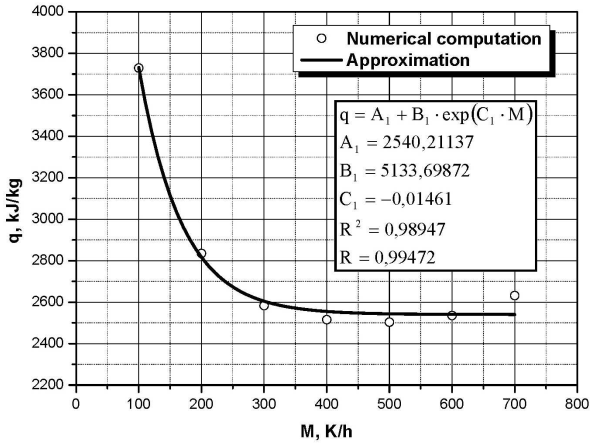

Fig. 4. Effect of heating rate on the consumption of heat in the model furnace

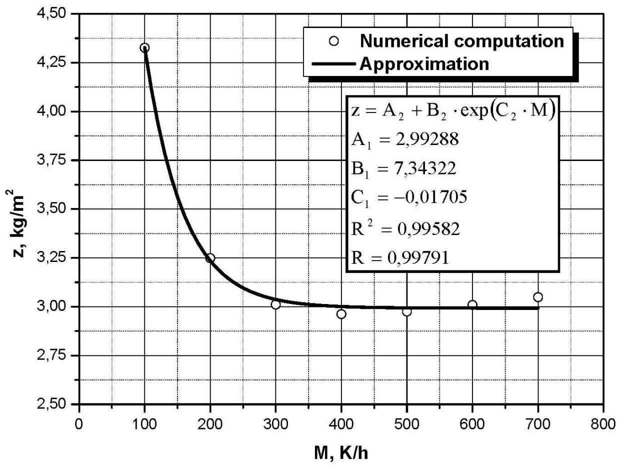

Fig. 5. Effect of heating rate on the loss of steel in the model furnace

The applied approximation relationships in the basic range of heating rate satisfactorily represent the discrete solution of the numerical model (Tables 1 and 2).

From Equation (11), we obtain:

$$M = \frac{1}{C_2} \cdot \ln\left(\frac{z - A_2}{B_2}\right) \quad \text{for } z > A_2. \tag{13}$$

By substituting relationship (13) in Equation (10), we obtain the relationship in the form of:

$$q = A_1 + B_1 \cdot \exp\left[P_1 \cdot \ln\left(P_2 \cdot z - P_3\right)\right] \quad \text{for } z > \frac{P_3}{P_2} \tag{14}$$

where:

$$P_1 = \frac{C_1}{C_2} = 0.85689, \quad P_2 = \frac{1}{B_2} = 0.13618,$$
$$P_3 = \frac{A_2}{B_2} = 0.40757.$$

Considering the above, relationship (14) can be written in ther following form:

$$q = 2540.2 + 5133.7 \cdot \exp\left[0.85689 \cdot \ln\left(0.13618 \cdot z - 0.40757\right)\right]. \tag{15}$$

The notation of the above relationship introduces some restrictions, namely it is true for $z > 2.99288$ kg/m^2 and therefore does not fully describe the range of data. However, the developed equation adequately represents the numerical computation results (Table 3). The maximum difference, $\Delta q_{\max}$, does not exceed 1.4%, while the mean description error, $\Delta q_{śr}$, is at the level of 0.5%.

TABLE 3

Comparison of the numerical computation results with the computation results obtained on the basis of the derived relationship

z kg/m^2	q (num. comp.) kJ/kg	q (relationship) kJ/kg	Δq %
3.009	2583.2	2567.3	0.616
3.011	2535.1	2570.1	1.381
3.049	2631.6	2619.0	0.479
3.249	2834.8	2829.7	0.180
4.326	3729.3	3730.0	0.019
$\Delta q_{śr}$, %			0.535

The values of the coefficients in Equation (14) can also be determined by direct approximation, while removing the restriction occurring in Equation (15). The approximation represented in Figure 6 describes the dependence of heat consumption on the steel loss with a correlation coefficient of $R = 0.999$.

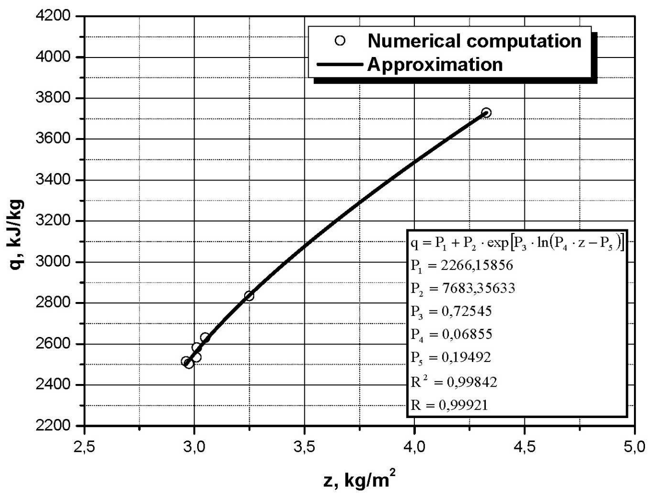

Fig. 6. Relationship of heat consumption as a function of steel loss

The values of the determined coefficients (Fig. 6) differ from those occurring in Equation (15).

In that case, it can be concluded that the direct approximation using Equation (14) offers better possibilities for the proper description of data.

Comparison of the numerical computation results with the results obtained from the approximation is summarized in Table 4.

TABLE 4

Comparison of the numerical computation results with the computation results obtained on the basis of approximation

z kg/m^2	q (num. comp.) kJ/kg	q (approxim.) kJ/kg	Δq %
2.962	2515.4	2500.2	0.604
2.975	2503.7	2518.5	0.591
3.009	2583.2	2564.3	0.732
3.011	2535.1	2566.9	1.254
3.049	2631.6	2615.0	0.631
3.249	2834.8	2837.3	0.088
4.326	3729.3	3729.0	0.008
$\Delta q_{śr}$, %			0.558

The correlation between heat consumption and the loss of steel for scale has also been described with a linear relationship, as follows:

$$q = 890.0 \cdot z - 109.1. \tag{16}$$

Equation (16) describes the discussed relationship with a correlation coefficient of $R = 0.997$ and a mean value difference of $q - \Delta q_{śr} = 1.0\%$. Thus, the description of this relationship by the linear equation can be considered very accurate.

5. Experimental

The aim of the experimental tests carried out on the laboratory testing stand (Fig. 7) was to confirm qualitatively the numerical computation results set out under point 5.

A basic element of the testing stand is an electric furnace (1) with heating chamber dimensions of 220x220x520 mm.

Temperature control was carried out based on electric power variation using a TROL – 9090 controller. The accuracy of furnace temperature control was ±1K, whereas the sample surface temperature was maintained according to the preset value.

The sample surface temperature was measured using a NiCr-Ni thermocouple with an EMT-302 temperature indicator.

The assumed gaseous atmosphere composition was secured by a burner (4) with a combustion chamber.

The power input was recorded using an electricity meter.

A detailed description of the measuring stand is provided in works [17, 18].

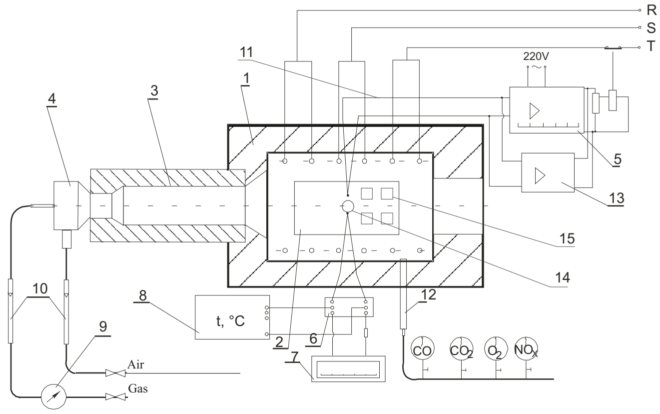

Fig. 7. Schematic diagram of the electric-gas furnace: 1 – furnace, 2 – refractory stand, 3 – combustion chamber, 4 – burner, 5 – temperature controller, 6 – compensation box, 7 – temperature recorder, 8 – EMT-302 temperature indicator, 9 – gas meter, 10 – rotameters, 11 – PtRh-Pt control thermocouple, 12 – combustion gas sampling probe, 13 – programmable temperature controller, 14 – reference sample with a NiCr-Ni thermocouple, 15 – test samples

The tests were conducted by modelling the two-stage heating process with a linear temperature increase in the heating-up period. The soaking stages were carried out with a constant surface temperature (t_p = 1250°C) for a time ensuring the final temperature difference on the charge cross-section (Δt_k = 50 K).

The variations of charge surface temperature during heating, for all heating rates (M = 100 to 600 K/h), were identical with those in the numerical computations of the effect of heating rate on heat consumption and steel loss.

The testing results are summarized in Table 5.

TABLE 5

Summary of experimental testing results

M K/h	Q_e kWh	z kg/m^2
100	88.9	4.424
200	67.4	3.532
300	60.1	3.344
400	57.2	3.285
500	55.7	3.316
600	57.8	3.352

The tests were conducted in conditions comparable to those of heating in electric chamber furnaces and differing considerably from the conditions prevailing in fuel-fired continuous furnaces. Therefore, the obtained testing results may not be used for quantitative comparisons.

Proceeding in a manner similar to that under point 4, the approximation of $Q_e = f(z)$ can be determined for the experimental results (Fig. 8).

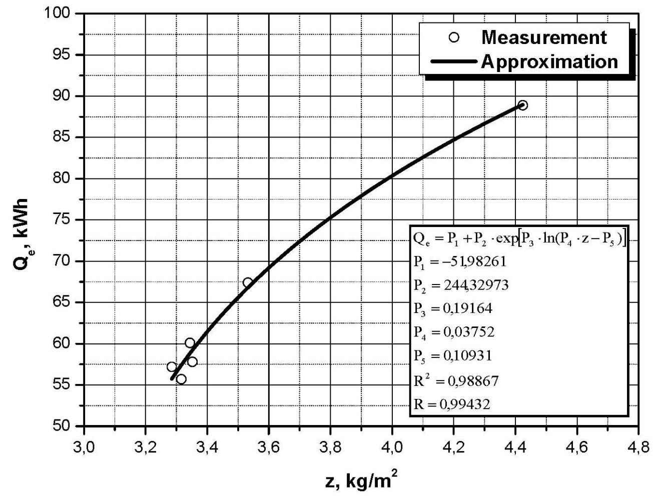

Fig. 8. Relationship of electrical energy consumption as a function of steel loss

Comparison of the testing results with the results obtained from the approximation is summarized in Table 6.

TABLE 6

Comparison of the measurement results
with the computation results obtained on the basis of approximation

z kg/m^2	Q_e (measurement) kWh	Q_e (approxim.) kWh	ΔQ_e %
3.285	57.2	55.8	2.448
3.316	55.7	57.4	3.052
3.344	60.1	58.8	2.163
3.352	57.8	59.2	2.422
3.532	67.4	66.8	0.890
4.424	88.9	89	0.112
$\Delta Q_{e,śr}$, %			1.848

The experimental testing results confirm qualitatively the numerical computation results.

6. Findings and conslusions

From the performed derivations and from the testing and computation results, the following conclusions can be drawn:

1. There is a close correlation between heat consumption and steel loss in steel charge heating processes.
2. It has been established that the relationship of heat consumption versus steel loss for the two-stage heating process can be represented in the following general form:

$$q = P_1 + P_2 \cdot \exp\left[P_3 \cdot \ln\left(P_4 \cdot z - P_5\right)\right]$$

3. The coefficients of the above equation are most conveniently determined by approximation.
4. The dependence of heat consumption on the steel loss is also accurately described by a linear equation.
5. The correlation between heat consumption and steel loss has been confirmed by experimental testing results.

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