Modeling of heating furnace thermal operations across steel loss in the heating process

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Abstract:
The paper presents industrial test results. The tests were carried out for different outputs resulting from the Department's production conditions. For a given furnace operating with a variable output, a correlation between the unit heat consumption index and the loss of steel for scale can be observed. With increasing process efficiency, unit heat consumption and steel loss decrease, while the coefficients of thermal efficiency improve. In views of the above, steel loss can be treated as the index of furnace thermal operation. From above mentioned, it is possible to model the furnace thermal operation indices through the steel loss.

Keywords: scale, loss of steel for scale, heating consumption, heating charge, heating technology.

Introduction
In the furnace calculation technique, thermal operation indices are used, which are defined in different ways [1]. The major indices of thermal operation of fuel-fired furnaces include: unit fuel consumption, unit heat consumption, and various types of thermal efficiency coefficients [2]. The indices defining the heating process quality include also the loss of steel for scale. The amount of scale forming in heating furnaces depend primarily on the charge surface temperature, the time of charge residence in the furnace and the excess air factor. Works [3, 4] made an attempt to establish a mathematical correlation between the unit heat consumption and the loss of steel for scale. Numerical computation [3] and industrial measurements [4] have shown that this correlation is best described by an equation of the following type:

\[ q = a + b \cdot \exp[c \cdot \ln(d \cdot z - f)] \]

where:
- \( a, b, c, d, f \) – empirical constants,
- \( q \) – unit heat consumption, kJ/kg,
- \( z \) – loss of steel for scale, kg/m².

In view of the above, the following proposition can be put forward: for a heating furnace operating with a variable output, the steel loss is a parameter defining not only the heating process quality, but also the quality of furnace thermal operation, and remains in relationship with other thermal indices. Based on so formulated thesis it can be assumed that the steel loss can provide a basis for the modelling (prediction) of heat consumption.

Furnace characteristics and the methodology of conducting tests
The subject of testing was a pusher furnace designed for the heating of steel billets. The furnace has 6 zones of automatic control. The maximum installed thermal power of the furnace is 62,35 WM and theoretically provides an output of 120 t/h. In practice, the furnace output depends on the Department's production conditions and usually does not exceed 75 t/h. The temperature of the heated-up charge ranges from 1150 to 1250°C, depending on steel grade.

The aim of the industrial tests was to:
- determine the dependence of heat consumption on the output,
- determine the dependence of steel loss on the output, and
- determine the correlation between the heat consumption and the steel loss.

Measurements were conducted for an established heating technology that secured a final charge surface temperature of 1250°C. A “cold” charge with a thickness of 225 and 250 mm, respectively, was heated in the furnace.

For the furnace under test, the numerical calculation of charge heating was also performed, which showed that the
applied distribution of temperatures in furnace zones provided a maximum output of approx. 90 t/h. The majority of measured quantities were read out from the control interface and furnace map printouts. The steel loss was determined using steel samples of dimensions of 45x45x100, which were heated up in the furnace. The steel loss value was calculated from the formula:

$$z = \frac{m_2 - m_1}{F},$$

where:
- \(m_1\) – sample mass before heating, kg,
- \(m_2\) – sample mass after heating, kg,
- \(F\) – sample surface area, m².

The unit heat consumption was calculated from the formula:

$$q = \frac{\dot{Q}_{chg}}{w},$$

where:
- \(\dot{Q}_{chg}\) – chemical heat of natural gas, kW,
- \(w\) – furnace operating at an output, kg/s.

**THE RESULTS OF INDUSTRIAL TESTS AND COMPUTATIONS**

The measurements of heat consumption and steel loss were carried out for output resulting from Department's production conditions. The tests carried out have enabled relationships to be derived, which describe the heat consumption and the steel loss as a function of process efficiency.

The dependence of heat consumption on the output is described by the following equation:

$$q = 1475,26 + 7623,64 \cdot \exp(-0,0739 \cdot w),$$

where:
- \(w\) – furnace operating at an output, t/h.

The effect of output on the steel loss is represented by the equation of the following form:

$$z = 4,44 + 24,60 \cdot \exp(-0,0431 \cdot w).$$

After substituting the transformed equation (5) in equation (4), a correlation between the unit heat consumption and the loss of steel for scale is obtained, as follows:

$$q = 1475,26 + 7623,64 \cdot \exp\{l(1,71 \cdot \ln(0,0406 \cdot z - 0,1805))\}. \quad (6)$$

**MODELLING OF FURNACE THERMAL OPERATION INDICES**

For purposes of the present work, a numerical model for the computation of steel loss in the heating process was developed. This model was referred to the conditions prevailing in the real pusher furnace, and its main objective was to compare model computation results with results obtained from measurements. The physical modelling of thermal phenomena that occur in industrial furnaces is practically infeasible. Establishing the correlation between the heat consumption and the loss of steel for scale provides an opportunity for modelling of thermal operation indices, as the steel loss is a quantity that can be calculated in a relatively simple way. The application of numerical methods using digital computers provides great freedom in modelling of steel losses for different heating cases.

The accurate calculation of steel losses is possible, provided that the following conditions are met:

a) the distribution of charge surface temperatures along the furnace length is known,

b) the time of charge residence in the furnace is known, and

c) the excess air factor in furnace zones, where charge oxidation occurs, is known.

Measured distribution of temperature on length of the furnace was basic to calculation the charge surface temperatures (fig. 1).

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**Fig. 1. Distribution of temperature of the furnace zones for studied heating technology**

The boundary condition of type II permits to calculate heating curves for any outputs (fig. 2). The furnace operating at an output is directly proportional to speed pushing of slabs for constant mass of the charge.

**Fig. 2. Computed heating curves for definite outputs**
For the furnace under test, the numerical calculation of charge heating was also performed, which showed that the applied distribution of temperatures in furnace zones provided a maximum output of approx. 90 t/h (fig. 3).

![Fig. 3. Distribution of the charge temperature on length of the furnace for output 90 t/h](image)

Final the charge surface temperature does not achieve required value 1250°C for project - output 120 t/h (fig. 4).

![Fig. 4. Distribution of the charge temperature on length of the furnace for output 120 t/h](image)

Calculations of steel loss were executed for chosen heating curves (w = 20, 25 ÷ 80 t/h). The steel loss after the successive time interval (k + 1) was computed from the formulae:

\[ z_{k+1} = \left( z_k^{1.333} + \Delta z^{1.333} \right)^{0.75}, \]  

(7)

\[ \Delta z^{1.333} = 2523 \cdot \Delta \tau \cdot \alpha^{1.333} \cdot \exp\left(-\frac{10000}{T_z}\right), \]  

(8)

where:
- \( T_z \) – substitute temperature for time interval, K,
- \( \Delta \tau \) – time interval, h,
- \( \alpha \) – excess air factor.

Equations (7) and (8) are model of steel oxygenation for heating furnaces, which are burning industrial gases.

The assumed excess air factor of \( \alpha = 1.08 \) corresponded to its average value in the heating and equalizing zones of the furnace examined.

In aim proof of thesis of present work, the heat consumption was computed using relationship (6).

The thermal efficiency coefficient of the technological process was determined from the relationship:

\[ \eta_t = \frac{Q_{m2} - Q_{m1}}{Q_{m2}} \cdot 100\% \]  

(9)

where:
- \( Q_{m1} \) – initial physical heat flux of the charge, KW,
- \( Q_{m2} \) – final physical heat flux of the charge, KW.

The results of studies and computations are shown in a graphical form. Figure 5 represents measurements and computations of steel loss as a function of process efficiency. The mean relative deviation of measurements results from computation results is: 5.16%. Following figure is verification of the model. The agreement of calculations with measurements was affirmed.

![Fig. 5. Steel loss as a function of output](image)

Figure 6 represents heat consumption as a function of output. The mean relative deviation of measurements results from computation results is: 5.31%. The agreement of calculations with measurements testifies about existence close correlation between steel loss and heat consumption.

![Fig. 6. Heat consumption as a function of output](image)
Figure 7 represents process efficiency as a function of output. The decrease of height consumption and steel loss causes high process efficiency.

![Figure 7. Process efficiency as a function of output](image)

**CONCLUSION**

From the performed measurements and computations, the following conclusions can be drawn:

- a close correlation exist between steel loss and furnace thermal operation indices,
- for a furnace operating at a variable output, steel loss is an important index of its thermal operation,
- it is possible to model the furnace thermal operation indices through the steel loss,
- the developed model adequately reproduces the thermal phenomena occurring in a real furnace.

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**REFERENCES**