EFFECT OF NUT COKE ON BLAST FURNACE SHAFT PERMEABILITY

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Abstract

The majority of blast furnaces nowadays use nut coke of different grain sizes primarily to reduce costs. Operation of many blast furnaces has proved the possibility of coke saving and increase of furnace productivity when using nut coke in mixture with burden but reasons and the mechanism of this phenomenon, and consequently the limit for nut coke consumption, are not very clear yet.

A method for quantitative analysis of the change in shaft permeability and furnace productivity when using nut coke - burden mixture has been developed. Calculations were conducted for a wide range of nut coke rate and grain size.

To validate the analytical model results, experimental simulations of gas flow conditions in the blast furnace shaft have been carried out using two cold rigs at RWTH Aachen, Germany, and at DNTU, Donetsk, Ukraine. The effect of layer thickness (both ratio of coke/burden layer thickness and their absolute value), gas velocity or flow rate and nut coke rate on the pressure drop in different packaged beds was examined. The combined effect of various factors such as the effect of nut coke rate for a changing flow rate and layer thickness was investigated as well.

Introduction

Grain size of metallurgical coke for a blast furnace should be big enough and the size distribution should be narrow to maintain stable operation and low coke rate. According to the requirements on coke properties its grain size should be mainly in the range of 40-80 mm. On the other hand the use of this big and relatively narrow fraction causes the increase in the coke costs due to the generation of big amount of under-sieve material. Prof. V.I. Loginov suggested in 1960s to charge fine under-sieve coke (today commonly known as nut coke) into the blast furnace in mixture with sinter (different from layered charging). This idea was successfully tested [1].

Presently the majority of blast furnaces use nut coke although its amount is very different: from 10-20 to 70-100 kg/tHM and more [2]. It has to be mentioned that there is no clear definition of nut coke grain size; in different countries and even companies its value is e.g., 10-30, 10-40 or 6-35 mm. Operation of many blast furnaces has proved the possibility of coke saving and increase of furnace productivity when using nut coke in mixture with burden but reasons and mechanism of this phenomenon are not very clear.

It was supposed that decrease in coke consumption while using nut coke is caused by higher reactivity of nut coke compared with metallurgical coke and that it reacts preferably with carbon dioxide and “protects” in this way metallurgical coke from the solution loss reaction in the shaft. But recent investigations both on industrial and lab scales did not prove this theory [3]. In [4] the change in reduction processes by using coke-ore mixed charging was studied. It was found that direct reduction is promoted in the cohesive zone and inhibited in the hearth and, hence, the heating hearth will be improved.
In this work the change in streaming conditions when charging nut coke has been studied.

Theoretical analysis of nut coke effect on shaft permeability and furnace productivity

The Darcy-Weisbach equation is commonly used to describe the pressure drop of the gas flow in a blast furnace (in N/m^2):

$$\Delta P = \psi \, (H/d) \, (1 - \varepsilon) / \varepsilon^3 \, (w^2 \cdot \rho), \qquad (1)$$

where, ψ: friction factor; $\psi = f(\mathrm{Re})$; Re: Reynolds number;
H: packed bed height, m;
d: equivalent grain diameter, m;
ε: voidage, m^3/m^3;
w: gas velocity, m/s;
ρ: gas density, kg/m^3.

The Darcy-Weisbach equation does not consider porosity of the materials. In [5] an effective voidage of materials (sinter, pellets, nut coke etc.) was introduced:

$$\varepsilon_e = \varepsilon + n \cdot V_g \cdot (1 - \varepsilon) \qquad (2)$$

where, n: porosity of material, unity fraction;
V_g: rate of pore volume accessible for gas flow, unity fraction.

Effective voidage of burden-nut coke mixture is calculated as follows:

$$\varepsilon_e^m = \varepsilon_e^b \cdot V_b + \varepsilon_e^{nc} \cdot V_{nc} \qquad (3)$$

where, ε_e^b and ε_e^{nc}: effective voidage of burden and nut coke respectively, %;

V_b and V_{nc}: volume rate of burden and nut coke in the mixture respectively, unity fraction.

Considering equations (2) and (3), the value of friction factor based on Ergun equation [6] for blast furnace conditions with average effective voidage in granular zone of 50% and sinter effective voidage of 29.3% will be:

for sinter $$\psi_s = 1.75 + 150/\mathrm{Re} = 1.75 + \frac{150}{1.414 \cdot \frac{wd}{v}} \tag{4}$$

for sinter-nut coke mixture (10 vol. % of nut coke in mixture) $$\psi_m = 1.75 + \frac{150}{1.490 \cdot \frac{wd}{v}} \tag{5}$$

where, ν: kinematical viscosity of gas in m^2/s.

To estimate the nut coke effect on gas permeability, it is not necessary to calculate the absolute values of pressure drop. It can be done by examination of the relationship of pressure drop for mix layer (ΔP_m) and for sinter layer without nut coke (ΔP_s).

$$\frac{\Delta P_m}{\Delta P_s} = \frac{\psi_m}{\psi_s} \cdot \frac{H_m \cdot (1-\varepsilon_{em}) \cdot \varepsilon_{es}^3}{H_s \cdot (1-\varepsilon_{es}) \cdot \varepsilon_{em}^3} \tag{6}$$

Study undertaken in [5] testified that values w, v and d do not change remarkably when part of coke is replaced with nut coke. Then, from equations (4) and (5) $\psi_m/\psi_s = 0.9871$ for above mentioned blast furnace conditions with 10 vol. % of nut coke in the mixture.

For a blast furnace with top diameter d_{top}=5.8 m, sinter layer H_s=0.12 m (ε_{es}=29.3%), total burden layer H_{ore}=0.30 m, 40 wt. % sinter in the burden, 10 vol. % nut coke in mixture with sinter: $\frac{\Delta P_m}{\Delta P_s} = 0.7333$, i.e. decrease in the pressure drop makes up 26.67%. Taking into account that nut coke is introduced with every second charge and mass rate of sinter in the burden is 40% (nut coke is mixed only with sinter), total decrease in the pressure drop in the dry shaft will be 26.67/2*0.40=5.33%. Calculations of change in gas permeability when using nut coke were conducted in a wide range of nut coke rate and size (Figure 1) [7]; nut coke rate is related to the total coke rate. It can be seen that the bigger grain size of nut coke is, the stronger its influence on change of the gas permeability is. The effect of nut coke on the burden permeability decreases with raising nut coke rate. Improvement of total gas permeability (burden and coke layers) is remarkable also at higher nut coke rate due to decrease in pressure drop of coke layers.

Furthermore calculations were performed for different sinter quality and blast furnace sizes. Table 1 shows ψ_m/ψ_s values for two sinters.

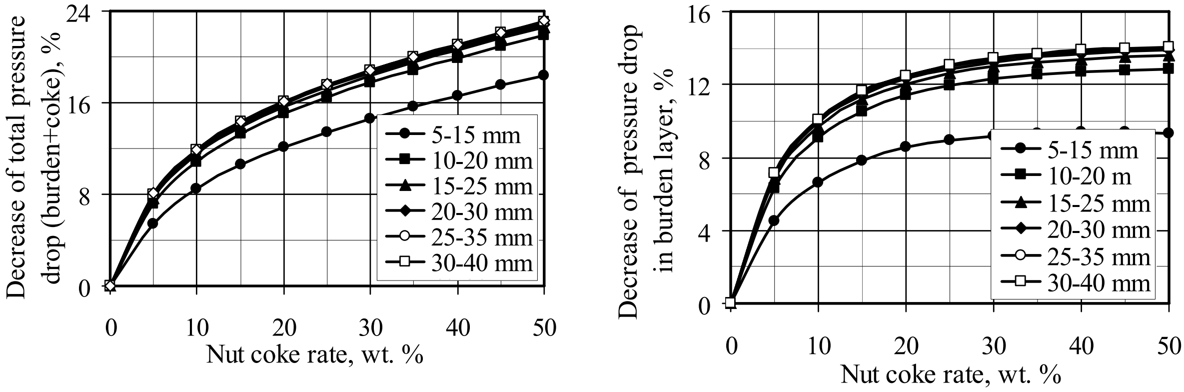


Figure 1. Decrease of pressure drop in BF "dry zone" when using nut coke of various size

Table 1. Friction factor ratio (ψ_m/ψ_s) for different conditions

	Sinter A (ε_e=29.3%)	Sinter B (ε_e=39.5%)
10 vol. % nut coke in mixture	0.9871	0.990
20 vol. % nut coke in mixture	0.9746	0.980

For a blast furnace with d_{top}=11.0 m, H_{ore}=0.79 m (nut coke is mixed with complete iron burden) using sinter of better quality (ε_e=39.5%) and 10 vol. % nut coke in mixture with iron burden:

$$\frac{\Delta P_m}{\Delta P_s} = 0.990 \cdot \frac{0.885 \cdot (1-0.420) \cdot 0.395^3}{0.790 \cdot (1-0.395) \cdot 0.420^3} = 0.8844$$

i.e. pressure drop makes up 11.56%. Nut coke is usually charged every second charge; therefore the average decrease in pressure drop makes up 5.8%.

It can be seen that figures for the large furnace operating with better sinter B and nut coke mixed with complete iron burden are close to figures for small furnace used sinter A and nut coke mixed with only sinter while the sinter rate is 40% of the burden weight. Detailed analysis showed that decrease of pressure drop when using nut coke is not remarkably influenced by blast furnace size and layer thickness but depends stronger on sinter quality; the higher sinter strength is, the less decrease of pressure drop for sinter-nut coke mixture is.

Change in the pressure drop is affected by gas velocity and blast volume:

$$\frac{\Delta P_1}{\Delta P_2} \approx \frac{w_1^2}{w_2^2} \approx \frac{Q_1^2}{Q_2^2} \qquad (7)$$

where, Q: blast volume, m^3/min.

Increase in the blast volume per unit of time raises the furnace productivity. Therefore dependence (7) can be extended:

$$\frac{\Delta P_1}{\Delta P_2} \approx \frac{w_1^2}{w_2^2} \approx \frac{Q_1^2}{Q_2^2} \approx \frac{p_1}{p_2} \qquad (8)$$

where, p: furnace productivity.

Increase in the blast volume per unit of time is limited by rise in the pressure drop [8]. Hence, decrease in pressure drop while using nut coke-burden mixture allows keeping sufficient gas permeability when increasing blast volume. This is a reason for higher productivity.

Decrease in total pressure drop when using 10-30 wt. % of nut coke with grain size of 5-15 mm makes up 7 and 9% respectively; for bigger nut coke size (20-40 mm) these values are about 9.5 and 13%. The reserve for increase of blast volume and, consequently, of productivity makes up:

at 10% nut coke rate (5-15 mm): $Q_2 = \sqrt{\Delta P_2 / \Delta P_1} \cdot Q_1 = \sqrt{0.93} \cdot Q_1 = 0.964 \cdot Q_1$ i.e. by 3.6%

at 30% nut coke rate (5-15 mm): $Q_2 = \sqrt{0.91} \cdot Q_1 = 0.954 \cdot Q_1$ i.e. by 4.6%.

For bigger nut coke size (20-40 mm), the reserve for increase of blast volume and productivity makes up 5.1 and 6.7% for 10 and 30% of nut coke rate respectively.

Assuming that solid materials occupy about 50% of the furnace height, blast furnace productivity can be increased by 1.8-3.35%. These figures reflect operation using sinter A.

Experimental study on shaft permeability when using nut coke

Facilities

Streaming conditions in the blast furnace shaft have been simulated using two cold models.

Lab rig at DNTU

The cold model with cylindrical stack dimensions of d=200 mm, H=500 mm simulates the granular zone of a blast furnace (Figure 2). Materials are placed on the grid with cell size of 1x1 mm. The pressure drop is measured for the height of packed material of 450 mm. U-tube manometer 6 is installed at the rectilinear pipeline section at a distance of more than 40 diameters of pipe in order to diminish the influence of local resistance and of the valve 2.

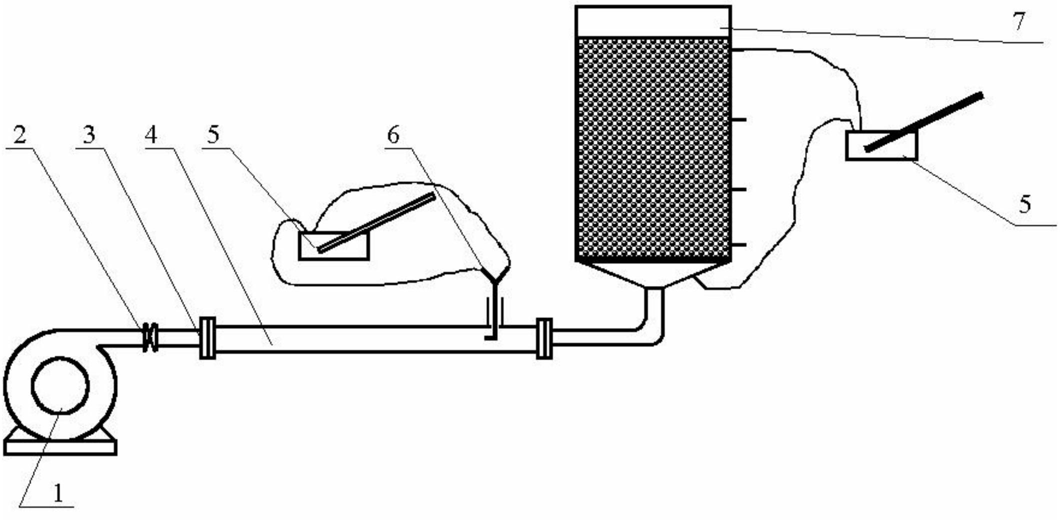


Figure 2. Scheme of DNTU model:
1 – air blower, 2 – valve, 3 – pipe adapting, 4 – rectilinear pipeline section, 5 – micro manometer, 6 – U-tube manometer, 7 – cylindrical stack for packed material

To simulate conditions in the granular blast furnace zone (top and “dry” shaft), Reynolds and Euler numbers (Re and Eu) were calculated considering following assumptions:

- Pressure along the “dry” shaft changes linearly;
- Sum of $CO+CO_2$ remains constant along the furnace height and mean CO_2 content in the lower part of the shaft is 3-5%;

- Temperature in the lower part of the shaft corresponds to the starting softening temperature of sinter and makes up 1150°C.

Air volume was calculated by following equation [7]:

$$Q = 3600 \cdot A \cdot F \cdot \sqrt{\frac{2 \cdot P_{din} \cdot g \cdot k_U}{\gamma}}, \quad \mathrm{m^3/h} \tag{9}$$

where, A: coefficient considering the gas velocity distribution along the model cross section;
F: area of cross section of the model's cylindrical stack, m^2;
P_{din}: dynamic pressure, mm water column;
k_u: coefficient of U-tube manometer;
γ: air density at a given temperature, kg/m^3.

Pre-tests showed that Eu number does not change remarkably when Re > 40. It means that for given conditions the similarity of flows is ensured when the air volume exceeds 85 m^3/h.

Lab rig at RWTH

The model is designed as a set of plexiglas segments that can be added or removed and thus the model can be easily adapted for various simulation conditions. Geometry of the model for current study is shown in Figure 3. Air is blown via six tuyeres and streams through the packaged bed. The air flow is measured and controlled by a flow meter. Pressure drop in the packaged bed is measured by a U-tube manometer. Distance from the tuyere level to the lower measuring point and the bottom of the stack is chosen to maintain vertical parallel streaming through the packaged bed.

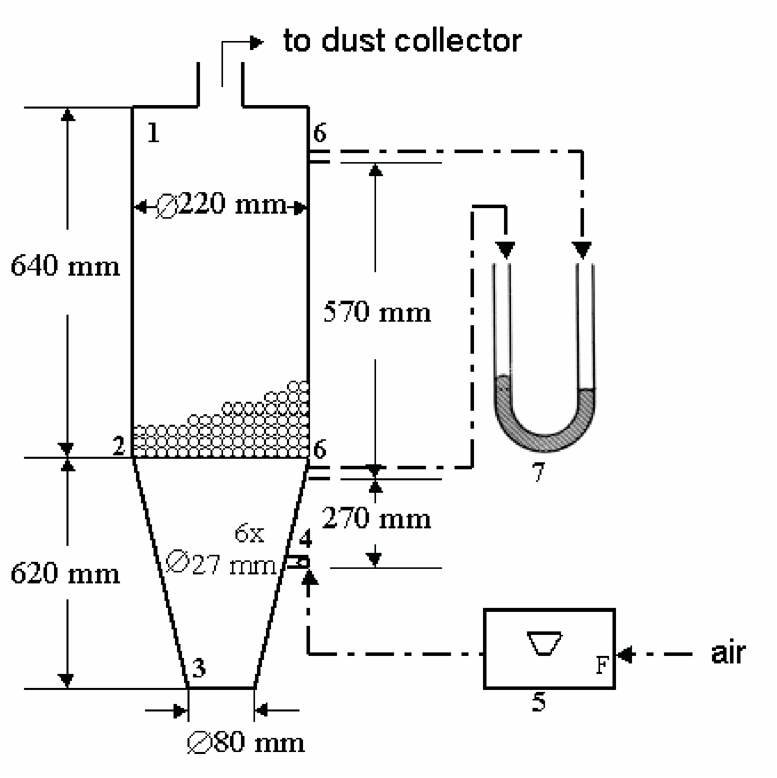


Figure 3. Scheme of RWTH model: 1- cylindrical stack for packed material, 2- grid, 3- conic hopper, 4- tuyeres, 5- variable area flow meter, 6-pressure drop measuring points, 7- U-tube manometer [9]

Materials

Characteristics of examined materials are shown in Table 2. Used grain sizes of materials simulate size ratios of sinter, nut coke and coke typical for a blast furnace.

Table 2. Grain size of materials

Material	DNTU rig	RWTH rig
Sinter	75% (mass): 3-5 mm 25% (mass): 1-2 mm	80% (mass): 8-12 mm 20% (mass): < 8 mm
Nut coke	3-5 mm	15-20 mm
Coke	-	35 mm, 45 mm

Test performance

Tests at DNTU rig

Value Q (eq. 9) that ensures similarity of flows was in the range of 90 to 115 m^3/h. Nut coke rate was changed from 0 to 40 wt. % of total coke consumption with interval of 2% in the range of 0-16% and 4% in the range of 16-40%. Coke rate was assumed to be 25% of the total raw material weight which is a representative value for Ukrainian blast furnaces. Pressure drop in the model was measured during the test. For each rate of nut coke six tests were performed with changing air volume.

Tests at RWTH rig

The effect of layer thickness, gas velocity or flow rate, and nut coke rate on the pressure drop in different packed beds was examined.

Two test series were conducted at the ratio of layer thickness of coke and burden (sinter and sinter-nut coke mixture) 1:1 (50 and 100 mm of each layer). This ratio corresponds roughly to coke-only operation. For the third test series the ratio of coke and burden layer thickness was set at 1:2 (50 and 100 mm respectively). This ratio represents the modern blast furnace operation in West Europe, e.g. at coke rate of 320 kg/tHM, PCI of 170 kg/tHM, iron burden of 1640 kg/tHM (when bulk densities of coke and sinter are 450 kg/m^3 and 1300 kg/m^3 respectively). Packed bed height was kept 500 mm in all tests. The ratio of the packed bed height to the stack diameter (2.27) is very close to that at DNTU rig (2.25) and corresponds roughly to H/D ratio of furnace “dry” zone. Voidage was kept on a constant low level.

Tests in both rigs were performed in the stationary packaged bed because no remarkable differences in pressure drop between stationary and moved packaged beds were founded [10].

Test results and discussion

DNTU results

Figure 4 shows dependence of air pressure drop in iron burden on the nut coke rate. Each dot on the graph corresponds to a mean value of six tests. For comparison, the calculated curve (for nut coke size of 15-25 mm) is plotted on the same graph.

Analysis of Figure 4 allows concluding that:

- Both trends and absolute values of experimental and calculated curves are close;
- First portions of nut coke (10-20% of coke consumption) decrease the pressure drop stronger (by 10% or more) compared with further portions.

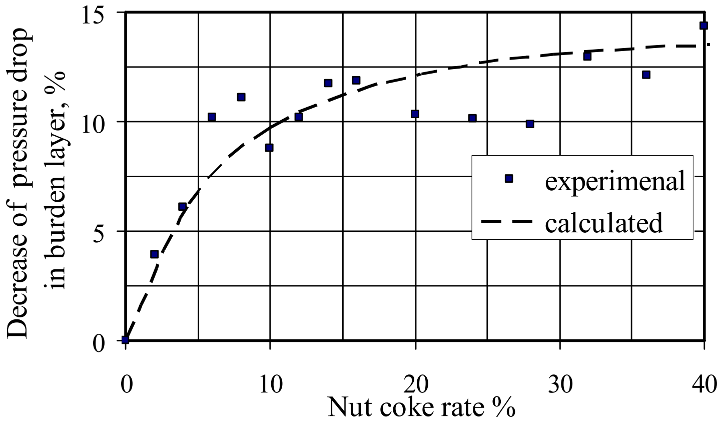
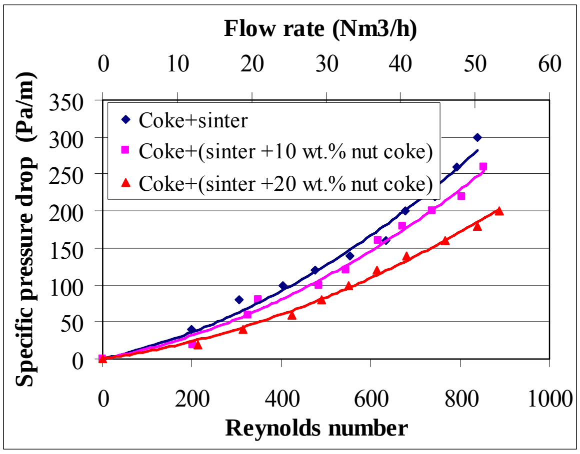


Figure 4. Effect of nut coke on the pressure drop

RWTH results

In Figures 5 and 6 it can be seen clearly that pressure drop decreases with rising nut coke rate in sinter–nut coke mixture. This effect becomes more remarkable at higher flow rates and Re numbers (for the blast furnace conditions 600 < Re < 800). Decrease of the coke layer thickness caused by low coke rate leads to increasing pressure drop. In other words, further decrease in coke rate is limited by the need to maintain suitable gas permeability.



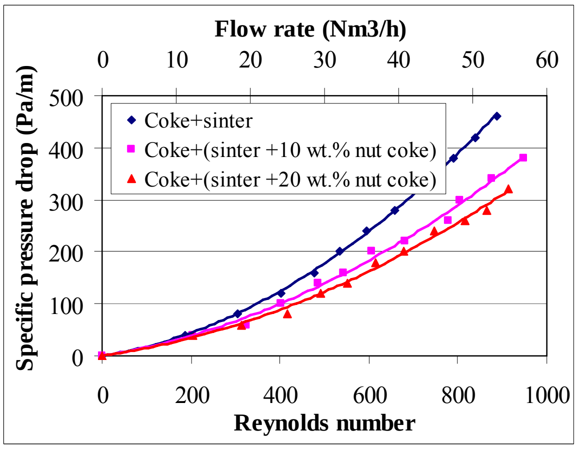


Figure 5. Dependence of specific pressure loss on Reynolds number and flow rate for coke/burden layer thickness ratio 1:1 (each layer of 100 mm)

Figure 6. Dependence of specific pressure loss on Reynolds number and flow rate for layer thickness ratio 1:2 (coke layers 50 mm, sinter and sinter-nut coke layers 100 mm)

Not only ratio of coke and burden layer thickness but also their absolute values affect gas permeability. Previous results are contradictory: in some studies the overall resistance to flow in layered charges decreased as the number of layers was increased, in other studies the increase in resistance to gas flow was observed when increasing the number of layers [11-12]. Present study proves that the overall pressure drop in the layered charged packaged bed is higher than the sum of the pressure drop in single layers because the number of boundary layers with higher pressure loss increases.

Figure 7 shows the effect of nut coke on pressure drop for different flow rate and layer thickness. It can be seen that discussed effects of nut coke rate and layer thickness become apparent at increasing flow rate. Further tests confirmed that at high flow rates even slight change in layer thickness affects the pressure drop significantly.

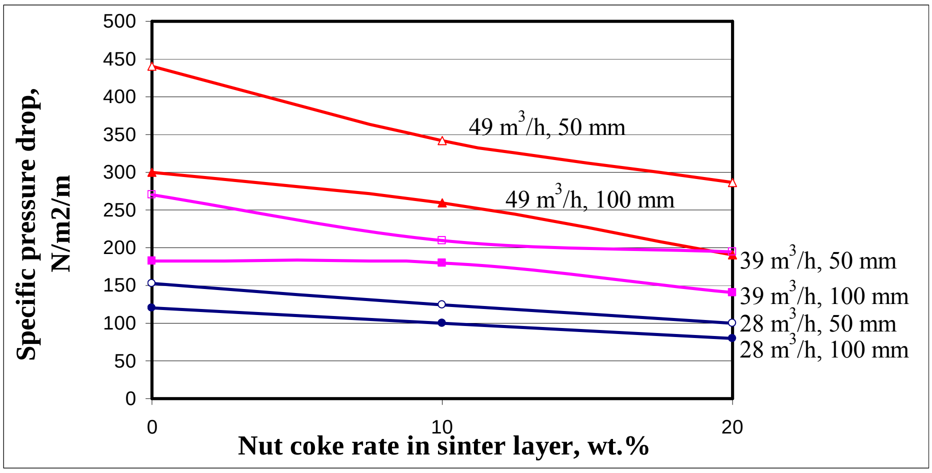


Figure 7. Effect of nut coke on specific pressure drop for various layer thickness and gas flow rates

In Figures 8 and 9 pressure drop is plotted vs. square of gas velocity for different layer thickness ratios. Results for the coke/sinter layer thickness 50/100 mm are very similar to those for 50/50 mm and are not presented here.

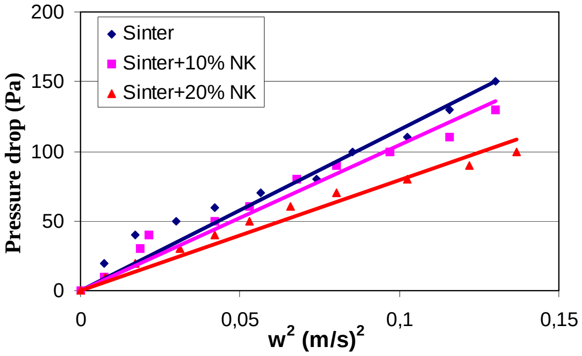


Figure 8. Effect of gas velocity on pressure drop for various nut coke rates at layer thickness of 100mm

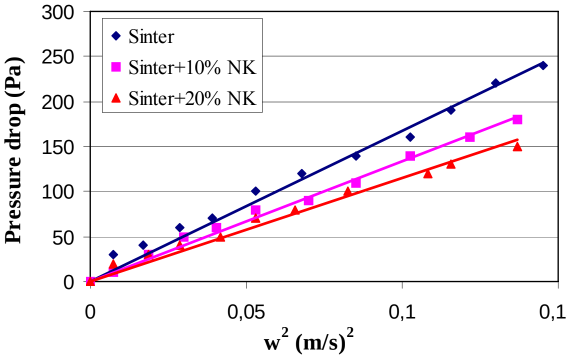


Figure 9. Effect of gas velocity on pressure drop for various nut coke rates at layer thickness of 50mm

Experimental results confirm linear dependence of pressure drop on flow rate and square of gas velocity (eq. (7)) for constant packaged bed voidage, height, equivalent diameter and gas density. Linear character of this dependence allows for estimation of the nut coke effect on pressure drop for the blast furnace conditions despite lower gas velocity in the lab tests. Test results for coke/sinter layer thickness ratio 1:2 (operating conditions with low coke rate of 310-320 kg/tHM and high PCI rate) showed that the pressure drop decreases by 20.5 and 31.5% when using 10 and 20 wt. % of nut coke in the sinter mixture respectively. Based on eq. (8), the reserve for increase of blast volume and, consequently, of productivity makes up:

$Q_2 = \sqrt{\Delta P_2 / \Delta P_1} \cdot Q_1 = \sqrt{0.795} \cdot Q_1 = 0.89 \cdot Q_1$ or 11.0% at 10 wt. % of nut coke in sinter layer,

$Q_2 = \sqrt{0.6823} \cdot Q_1 = 0.826 \cdot Q_1$ or 17.4% at 20 wt. % of nut coke in sinter layer.

Assuming that solid materials occupy about 70% of the furnace working height (it corresponds to above mentioned operating conditions and centre coke charging), blast furnace productivity can be increased by 7.7-12.2% for 10 and 20 wt. % nut coke in sinter layer or by 1.5-2.5% for 10 and 20 wt. % nut coke to coke rate respectively.

Conclusions

Theoretical analysis testified that the bigger grain size of nut coke, the stronger its influence on change of gas permeability. The effect of nut coke on burden permeability decreases with rising nut coke rate. Blast furnace productivity can be increased by 1.8-3.35% when using 10-30 wt. % of nut coke and sinter with lowered sinter strength.

Analytical results were confirmed by lab experiments. Pressure drop decreases with rising nut coke rate. The total pressure drop in the layered charged packaged bed is higher than the sum of the pressure drop in single layers. Effects of nut coke rate and layer thickness become apparent at increasing flow rate. Blast furnace productivity can be increased by 1.5-2.5% for 10 and 20 wt. % nut coke to coke rate respectively.

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