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SELECTIVE NON-CATALYTIC REDUCTION OF NITROGEN OXIDES IN THE PRODUCTION OF IRON ORE PELLETS

Purpose. Using mathematical modeling, to assess the feasibility of introducing a Selective Non-Catalytic Reduction (SNCR) system as a measure to reduce nitrogen oxide emissions from the production of iron ore pellets. To determine the peculiarities of using ammonia solution and urea solution as reagents for the SNCR process, the influence of the injection of these reagents on the temperature regime during iron pellet production, as well as assess the expected efficiency of the SNCR method for purification of exhaust gases from nitrogen oxides.

Methodology. The research results have been obtained using CFD-modeling in the ANSYS Fluent software package. To model this process, a computational domain is constructed, which corresponds in size to the preheating zone (PRE zone) of the actual iron pellet production plant. Two series of calculations are performed for this domain: the first, without adding a reagent, and the second, with a urea solution as a reagent for the SNCR system.

Findings. For the first series of calculations, the temperature field and the pressure field in the computational domain is obtained. Experimental research makes it possible to assert that the physical conditions of the mathematical model are close to those at a real plant for the production of pellets. In the second series of calculations, the temperature field in the computational domain is obtained and the influence of the reagent injection of the SNCR system is determined, namely, the temperature decrease in the PRE zone of the pellet production plant by 10–25 °C. The expected efficiency of reduction of nitrogen oxides using a 50 % urea solution is about 60 %.

Originality. It has been revealed that the process of urea solution evaporation is intense, which accelerates the beginning of urea decomposition and, accordingly, the reduction reaction of nitrogen oxides. The temperature drop in the zone of moisture evaporation does not exceed 10–25 °C. The reagent injection (50 % urea solution) with a consumption of 219 kg/h does not significantly affect the temperature regime in the PRE zone. Modeling the chemical reactions of the SNCR process with the injection of 50 % urea solution droplets through lances into the PRE zone chamber indicates a 60 % reduction in nitrogen oxide emissions.

Practical value. The introduction of the SNCR system at pellet production plant can reduce nitrogen oxide emissions, which will have a positive impact on the environmental situation in metallurgical regions.

Keywords: iron ore pellets, selective non-catalytic reduction, nitrogen oxides, denitrification, exhaust gases

Introduction. In modern conditions, improving the state of the environment is one of the main purposes of reconstruction and modernization of production. The European Commission in 2021 adopted the EU Action Plan, Towards Zero Pollution for air, water and soil [1, 2], which sets specific targets for significant emission reductions by 2050 with a revision of Directive 2010/75/EC requirements on industrial emissions [3]. For the EU countries, where more than 52 000 large polluting enterprises operate, the target has been set to significantly reduce emissions of sulfur dioxide, nitrogen oxides, particulate matter, and others in accordance with Directive (EU) 2016/2284 on the reduction of national emissions of certain atmospheric pollutants [4].

Nitrogen oxides NO_x (a mixture of NO oxide and NO₂ di-oxide), which are formed at high temperatures [5] as a result of gas-phase reactions of nitrogen and oxygen [6, 7], are pollutants. Their release into the atmospheric air leads to the formation of acid rain and deterioration in human health and environmental conditions [8]. Therefore, the NO_x content in the exhaust gases is regulated by the relevant environmental legislation. In Ukraine, the general standard for maximum permissible emissions of nitrogen oxides is 500 mg/m³ [9]. For large combustion plants with a rated thermal capacity of more than 50 MW, the maximum nitrogen oxide content is regulated from 1300 mg/m³ for existing coal-fired boilers to 100 mg/m³ for new gas-fired boilers [10].

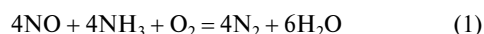
To reduce NO_x emissions, both primary measures and secondary measures are used: the primary measures [6, 8] (oper-

ational-technological methods) are aimed at creating conditions for less formation of nitrogen oxides, whereas by means of secondary measures the NO_x content in the exhaust gases is reduced due to the chemical interaction of formed NO_x with reagents [7, 11]. The application of a measure or series of measures to reduce nitrogen oxide emissions is determined by the technological conditions of production, the required level of NO_x emission reduction, the availability of the reagent, and so on [11].

Literature review. Specificity of iron ore pellet production. Production of iron ore pellets includes the processes of their heating and calcinating at high temperatures [12]. Fig. 1 shows a typical technological scheme for obtaining pellets [13, 14].

The raw iron ore travels on a grate through the heat exchange chambers towards the exhaust gases coming out of the rotary kiln, and enters the kiln burner. The rotary kiln burns fuel to generate the energy necessary to calcinate the pellets. After the kiln, the pellets are fed into the cooler and then loaded to consumers.

The high temperature in the rotary kiln causes a high content of nitrogen oxides in the exhaust gases. Given the complex technological scheme and the lack of practical possibility of applying the primary measures to reduce NO_x emissions, provided that the required quality of pellets is ensured, virtually the only way to denitrify exhaust gases is the use of secondary measures. These measures include selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) of nitrogen oxides to molecular nitrogen. They are based on the reduction of NO_x with ammonia NH₃ or urea (NH₂)₂CO to molecular nitrogen N₂



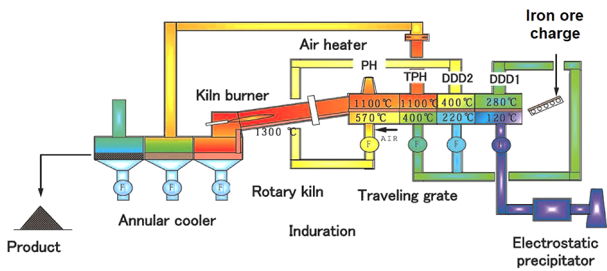
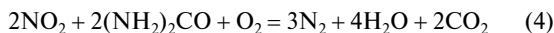
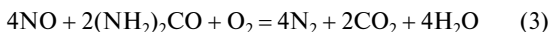
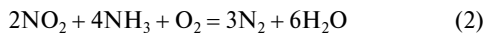


Fig. 1. Typical flow and temperature scheme for pellet production

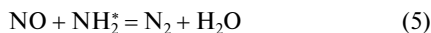


Since the content of nitrogen oxide NO in gaseous products of fuel combustion is almost 20 times higher than the content of nitrogen dioxide NO₂ [6, 7], then reactions (1, 3) will be taken into account in further reduction processes.

The fundamental difference between SCR and SNCR technologies is that in SCR processes effective NO_x reduction occurs on the catalyst surface at temperatures from 200 to 500 °C, and in SNCR processes – in the gas phase at a temperature of 1050–850 °C. The efficiency of SCR technology reaches 90 %, and the efficiency of SNCR technology – up to 70 % [11].

The main advantage of the SNCR method over the SCR method is that there is no need to use a catalyst and equipment to place it in a certain place of the technological process. In this regard, according to various estimates, the cost of construction of SNCR systems is about 10 times lower than that of SCR installations [12].

Specificity of selective non-catalytic reduction (SNCR). The chemical principle for the selective reduction of nitrogen oxides is the reaction between NO_x and an amine radical NH₂^{*}. The products of this reduction are molecular nitrogen N₂ and water vapor H₂O



The amine radical NH₂^{*} is formed as a result of the reaction between ammonia NH₃ and the hydroxyl radical OH^{*} [15, 16]



Without a catalyst, the NO reduction reaction preferably occurs in a temperature range of 850–1050 °C, which is typical for SNCR process. The sources for radical NH₂^{*} generation are three reagents – ammonia solutions (Ammonia Water), carbamide (Urea) and isocyanic acid (Cyanuric Acid). The reaction scheme, shown in Fig. 2, illustrates the individual reactions and the relationship between them. This SNCR scheme is simplified. In fact, there are about 150 chemical reactions [16].

The reagent is fed into the hot exhaust gases through nozzles or lances, which are set on the walls of the process equip-

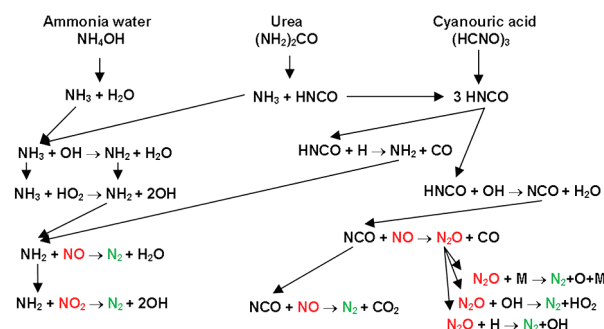


Fig. 2. Basic chemical reactions of the SNCR process [16]

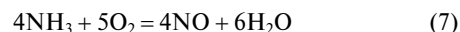
ment. The injection of droplets leads to mixing the reagent with the exhaust gases. The heat from the hot exhaust gases provides the energy for the evaporation of moisture droplets and the reactions of the reduction process. The NO_x molecules are reduced to N₂, and the purified exhaust gases are sent out to the atmospheric air.

The main factors influencing the efficiency of reducing NO_x emissions using SNCR technology are [15]:

- temperature range of the reaction;
 - sufficient residence time in the optimum temperature range;
 - degree of mixing the reagent and exhaust gases;
 - NO_x initial concentration level;
 - stoichiometric ratio of nitrogen oxides to the reagent.
- In laboratory conditions (isolated system, perfect mixing, unlimited residence time), the efficiency of the SNCR ammonia process exceeds 90 %. Ideal temperature is 970 °C and residence time is at least 0.5 s.

In real systems, the NO_x reduction reaction occurs within a certain temperature range, since heat is required to start the reaction (Fig. 3). At low temperatures, the reaction rate of nitrogen oxide with ammonia is low, and ammonia passes through the reaction zone (there is a slip of NH₃).

At high temperatures, the reagent can oxidize itself, which leads to the formation of additional nitrogen oxides NO_x



The temperature range of the SNCR process depends on the reagent. For ammonia solution, the optimum temperature range is 870–1100 °C with a peak value of 950 °C. For a urea solution, the optimum temperature range is 900–1150 °C with a peak efficiency value of 1010 °C [15].

The residence time is the length of time during which the reagents are in the core (chemical reactor). Before the reagents leave the core, all stages of the SNCR process must be completed, including:

- mixing the reagent solution with hot exhaust gases;
- evaporation of water;
- decomposition of urea to ammonia and amine radicals;
- decomposition of ammonia into an amine radical;
- chemical reactions of NO_x reduction.

Increasing the residence time for mass transfer and chemical reactions in general increases the NO_x removal. In addition, if the reaction temperature range is narrowed, then more residence time is required to achieve the same level of nitrogen oxide reduction.

To intensify the reduction reaction, the reagent must be sprayed and mixed throughout the entire volume of exhaust gases. When using ammonia, dispersion should occur rapidly due to its volatile properties. Mixing requirements are usually

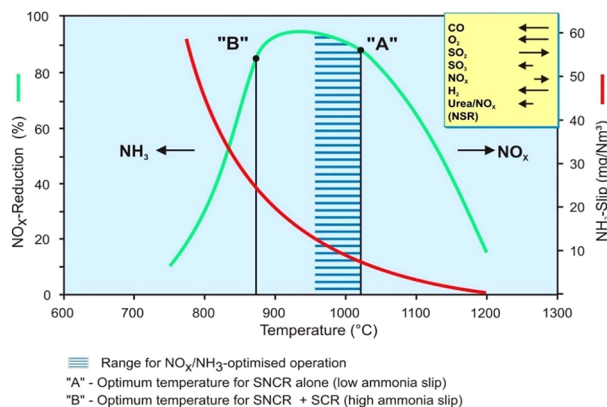


Fig. 3. Reduction of NO_x as a function of temperature [17]:

A – optimum temperature for the SNCR process (low ammonia slip); B – optimum temperature for the SNCR + SCR process (high ammonia slip)

specific to each process scheme and depend on the gas and air flow profiles. Mixing is done by an injection system. The injectors spray the reagent and set the spray angle, velocity and direction of the injected reagent. These systems are specific to each kiln and reagent.

To improve dispersion, the reagent is sprayed dropwise through specially designed nozzles that optimize the size and distribution of the droplets. Evaporation time and trajectory are a function of the droplet diameter. Larger droplets have greater impulse and penetrate further into the flow of exhaust gases. However, they also need more time to evaporate, increasing the required residence time. Inadequate mixing leads to insufficient NO_x reduction. Mixing can be improved in several ways, for example:

- increasing the energy transferred to the droplets;
- increasing the number of nozzles (lances);
- changing the design of the spray nozzles to optimize the size of the solution droplets, their distribution by size, the angle of spraying and its direction.

The inlet NO_x concentration is the concentration of nitrogen oxides in the exhaust gases at the inlet of the SNCR zone. The concentration of reagents affects the rate of the NO_x reduction reaction – it decreases with a decrease in the reagent concentration. This is due to thermodynamic peculiarities limiting the reduction process at low NO_x concentrations. For low concentrations at the inlet, the optimum reaction temperature is lower; therefore, the percentage of NO_x reduction is lower.

The normalized stoichiometric ratio (NSR) determines the amount of reagent required to achieve the target NO_x reduction. Based on reaction (1, 3), it is theoretically possible to remove two moles of NO_x with two moles of ammonia and one mole of urea. In practice, it is necessary to add more than the theoretical amount of reagent into the exhaust gases in order to obtain a specific level of NO_x reduction. This is conditioned by the complexity of the chemical reactions themselves, including NO_x and the added reagent, as well as restrictions on the mixing of the reagent and exhaust gases. Typical NSR values are from 0.5 to 3.0 moles of ammonia per mole of NO_x [10]. Since capital and operating costs directly depend on the amount of reagent, determining the optimal NSR value is crucial. Factors influencing the NSR value include:

- percentage of NO_x reduction;
- initial NO_x concentration in the exhaust gases;
- temperature and residence time appropriate for NO_x reduction reactions;
- achievable degree of mixing in the apparatus;
- permissible ammonia slip;
- rates of competing chemical reactions.

Typical NSR values in practice require much more reagent to be added than the stoichiometric ratio requires. In addition, the amount of recovered NO_x oxides is usually much less than the amount of initial NO_x. This leaves most of the added reagent unreacted. Most of the excess reagent used in the process is disposed of by other chemicals and reactions. However, some amount remains in the exhaust gases in the form of ammonia slip.

Purpose. To conduct a mathematical study of the specifics of the selective non-catalytic reduction (SNCR) process implementation as a measure to reduce emissions of nitrogen oxides formed during the production of pellets. To determine the peculiarities of using the ammonia solution and urea solution as reagents of the SNCR process. In addition, to reveal the influence of the injection of these reagents on the temperature regime of iron ore pellet production and assess the expected efficiency of the SNCR method for purification of exhaust gases from nitrogen oxides.

Methods. The research results have been obtained using CFD-modeling in the ANSYS-FLUENT software package. To model this process, a computational domain is constructed, which corresponds in size to the PRE-zone of the actual

iron pellet production plant. Two series of calculations are performed for this domain: the first, without adding a reagent, to clarify the physical parameters without external influence, and the second, with the addition of a urea solution as a reagent for the SNCR system.

Results. Reagent selection. The cost of the reagent makes most of the operating costs of the SNCR process. Both ammonia and urea have been successfully used as a reagent in the SNCR process.

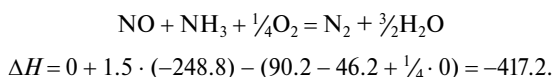
Ammonia is more reactive and cheaper than urea. It is a toxic gas that dissolves easily in water at ambient temperature. An aqueous solution with a 25 % weight content of NH₃ is considered the optimal ammonia water for SNCR. However, as the temperature rises, ammonia evaporates quickly from the water. Strict safety requirements, such as protective equipment in the tank, ammonia sensors, wind direction indicators, gas exchange pipes, emergency showers, and others, must be observed when storing ammonia water [15].

Urea is usually used in the form of a 50 % aqueous solution, which is fed into the boiler and evaporates by its heat. The urea solution should be constantly heated due to its freezing point of 17.8 °C. Urea can be used in the form of granules, which minimizes the volume of storage and transportation. When producing an aqueous solution for SNCR, it should be mixed with water at the enterprise. Due to the chemical bonds of ammonia in the urea molecule, solutions can be heated to 106 °C without evaporation of gaseous ammonia. The decomposition of urea into ammonia and carbon dioxide begins at least at 130 °C and reaches a maximum at about 380 °C. Such high temperatures are not achieved when storing chemicals, which means that the safety measures required for ammonia water are not required here [15]. Therefore, a 50 % urea solution is chosen as the main reagent.

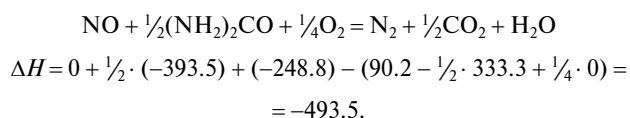
The SNCR process energetics. Since the reagent (ammonia or urea) is supplied to the reaction zone in the form of droplets of an aqueous solution, the process of reduction of nitrogen oxides is accompanied by energy-consuming evaporation of moisture droplets ($Q_{vap} = 2382$ kJ/kg of water at 50 °C) or 7146 kJ/kg of 25 % ammonia solution or 2382 kJ/kg of 50 % urea solution.

The general chemical reactions of the SNCR process are exothermic. The change in enthalpy of chemical reactions is measured in kJ per 1 mol NO:

For ammonia



For urea



The enthalpies of both reactions are significant and close in value.

According to the stoichiometry of reaction (1), 33.3 mol of NH₃ or 2.266 kg of 25 % ammonia solution are required to reduce 1 kg or 33.3 mol of NO. The thermal effect of the chemical reaction (1) is 13,906.7 kJ/kg NO, and 4,049.4 kJ/kg NO is required to evaporate water from 2.266 kg of a 25 % ammonia solution. As a result, 9.86 MJ/kg NO thermal energy is released.

To reduce 1 kg or 33.3 mol of NO according to reaction (3), 16.67 mol of urea or 2.0 kg of a 50 % urea solution is required. The thermal effect of the chemical reaction (3) is 16,450.0 kJ/kg NO, and to evaporate 1 kg of water from 2.0 kg of 50 % (NH₂)₂CO solution, 2382.0 kJ/kg NO is required. As a result, a thermal energy of 12.07 MJ/kg NO is released.

Thus, in general, the use of the SNCR process will not lead to a decrease in temperature in the reaction zone. Although, at

the stages of the radical NH_2^* formation, the energy consumption for chemical reactions is significant:

1. Endothermic reaction of generation of hydrogen radicals H^* (enthalpy of formation $\Delta H = 217 \text{ kJ/mol}$) and hydroxyl OH^* (enthalpy of formation $\Delta H = 39.3 \text{ kJ/mol}$) from water vapor molecule. The change in enthalpy of chemical reactions (ΔH) is measured in kJ/mol



$$\Delta H = 217 + 39.3 - (-248.8) = 505.1.$$

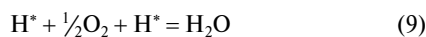
2. The amine radical formation according to reaction (6) is a weak exothermic reaction

$$\Delta H = 174 + (-248.8) - 39.3 - (-46.2) = -67.9.$$

3. Exothermic reduction reaction (5)

$$\Delta H = 0 + (-248.8) - 174 - 90.2 = -513.$$

4. Deactivation of hydrogen radicals (exothermic reaction)



$$\Delta H = (-248.8) - 217 - 217 - 0 = -682.8.$$

Modeling of SNCR placement. The SNCR system placement, as well as temperature and concentration fields are modelled using the ANSYS Fluent software package.

The SNCR system is set in the upper part of the PRE zone chamber of the movable grate at the outlet of exhaust gases from the rotary kiln (Fig. 4).

The scheme of the PRE zone chamber of the movable grate at the outlet of exhaust gases from the rotary kiln is shown in Fig. 5.

Based on the actual structural dimensions of the PRE zone, the geometry of the computational domain is created. The existing geometry is divided by the computational grid (Fig. 6) for computer modelling using CFD.

The computational domain consists of three zones: the zone above the material layer (gas inlet), the zone of the po-

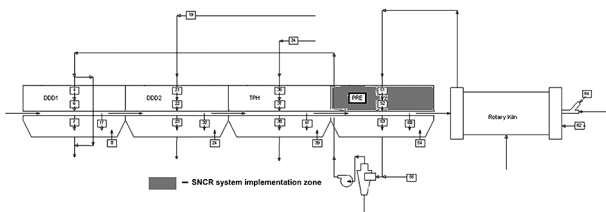


Fig. 4. The reagent injection zone of the SNCR system

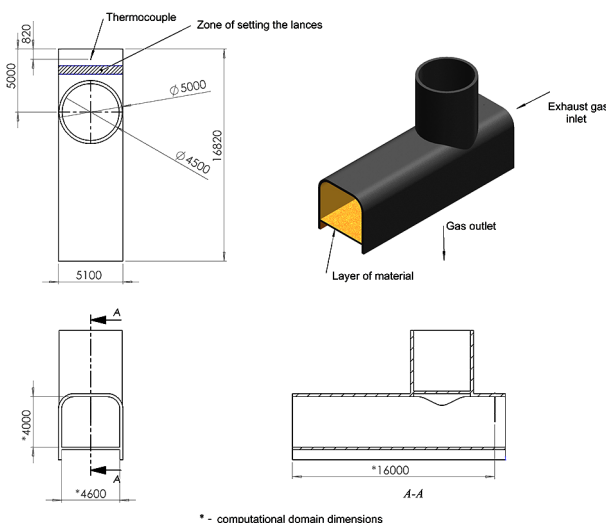


Fig. 5. Scheme of the preheating zone chamber

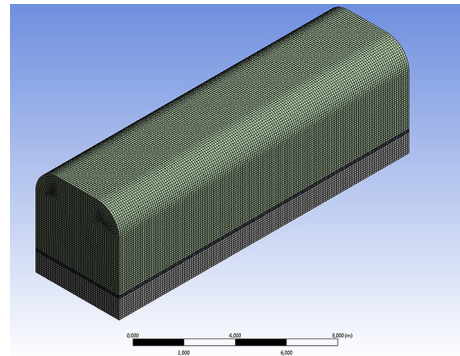


Fig. 6. Computational domain together with the grid

rous material layer and the zone under the material layer (gas outlet). The size of the grid cell in the zone of the porous material is reduced by 2 times to detail the process in the layer.

Inlet of hot exhaust gases:

Exhaust gas consumption: 100 kg/s (6000 kg/min);

Exhaust gas temperature: 1405K (1132 °C);

The composition of the exhaust gases (wt.):

$\text{N}_2 = 76.4 \%$;

$\text{O}_2 = 18.0 \%$;

$\text{H}_2\text{O} = 2.9 \%$;

$\text{CO}_2 = 2.5 \%$;

$\text{NO} = 0.2 \%$.

Outlet of hot flue gases: Rarefaction of flue gases at the outlet: -3000 Pa (-306 mmAq).

Material layer parameters.

The material layer temperature at the inlet of the PRE zone: 800 K (527 °C);

The material layer temperature at the outlet of the PRE zone: 1350 K (1077 °C);

Modeling the temperature and pressure fields in the PRE zone chamber without SNCR.

To test the PRE zone model, temperature fields (Fig. 7) and pressure fields (Fig. 8) are calculated to represent the heat exchange processes between the product layers, as well as to adjust the layer porosity for achieving rarefaction over the material layer ($3\text{--}12 \text{ mmAq}$).

As a result of modeling, it can be seen that heat exchange between the material layer and flue gases occurs, and the ma-

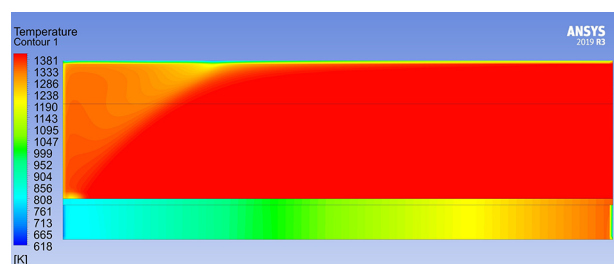


Fig. 7. Temperature field in the longitudinal section of the PRE zone

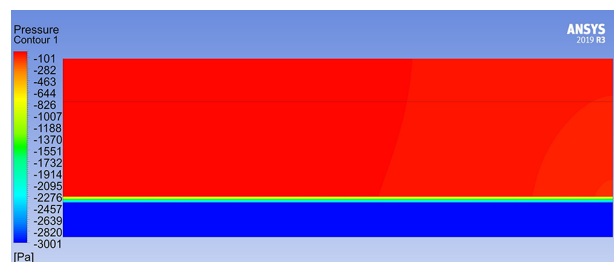


Fig. 8. Pressure field in the longitudinal section of the PRE zone

terial layer porosity satisfies the condition of flue gas rarefaction over the material layer – 3–12 mmAq (the difference is –100 PA or –10.2 mmAq).

Modeling the process of the reagent injection into the SNCR system. The reagent for the SNCR system on the pellet calcinating kiln is a urea solution with urea mass concentration of 50 % and a total consumption of 219 kg/h. The solution temperature is 293 K (20 °C). The reagent is injected into the zone above the material layer through 8 lances with consumption of 27.36 kg/h for each. The lances are located along the perimeter of the upper part of the inlet zone at two levels as the flue gases move (0.7 and 1.0 m from the flue gas inlet) (Fig. 9). It is assumed that the average diameter of the reagent droplets is 300 μm, and the angle of each nozzle opening is 15°.

When modeling the SNCR process, the temperature fields (Figs. 10 and 11) and the temperature of the reagent droplets are calculated. When calculating the temperature fields, the heating of air with a consumption of 500 kg/h (220 kg/h for spraying the reagent and 280 kg/h for cooling the lances) is not taken into account. The approximate heat consumption for evaporation of 110 kg/h of water, half of the reagent consumption (50 % urea solution), is 248,600 kJ/h. And the heat consumption for heating the air from a temperature of 20 °C to the highest temperature in this zone of 1,132 °C, is 560 kJ/h and 0.2 % of the heat consumed for water evaporation.

It can be seen in Figs. 10 and 11 that when the reagent droplets are injected, the temperature decrease is insignificant (10–25 °C), which does not affect the main technological process and the SNCR process. In addition, in Fig. 11, the degree of overlap of the PRE zone cross-section with the injected reagent can be seen.

The evaporation process of reagent droplets can be seen in Figs. 12 and 13, which show the temperature of the reagent droplets and their concentration, respectively.

There is an intensive process of droplet evaporation, which allows urea to decompose into reactive NH₂-components only after the complete evaporation of water [17].

The results of modeling the concentration fields of nitrogen oxide NO, when droplets of urea solution are injected into

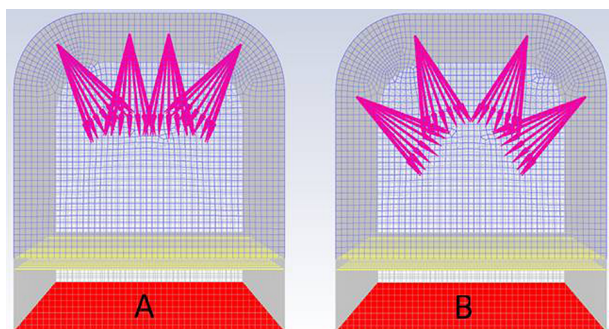


Fig. 9. Arrangement of two levels of lances and their angles for reagent injection along the cross section of the PRE zone (distance from an inlet of flue gases: A – 0.7 m; B – 1.0 m)

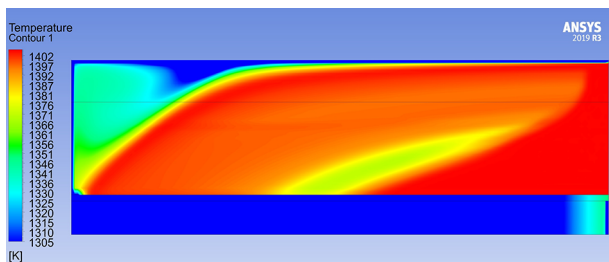


Fig. 10. Temperature field in the longitudinal section of the PRE zone when adding the reagent in the temperature range of 1305–1405 K

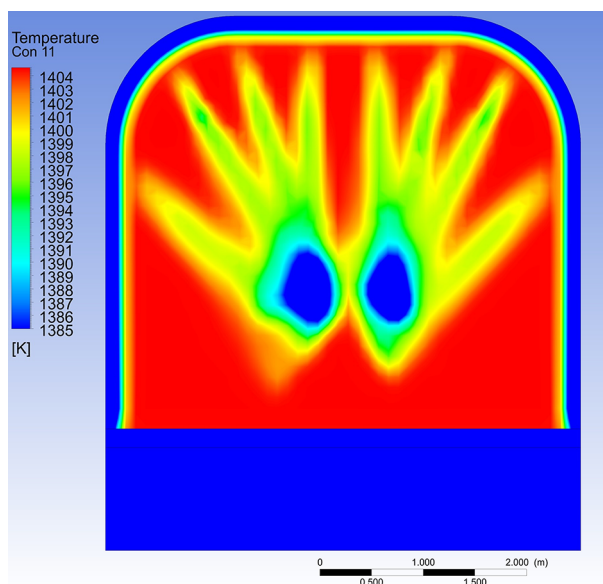


Fig. 11. Temperature field in the cross section of the PRE zone at a distance of 5 m from the flue gas inlet in the temperature range of 1,385–1,405 K

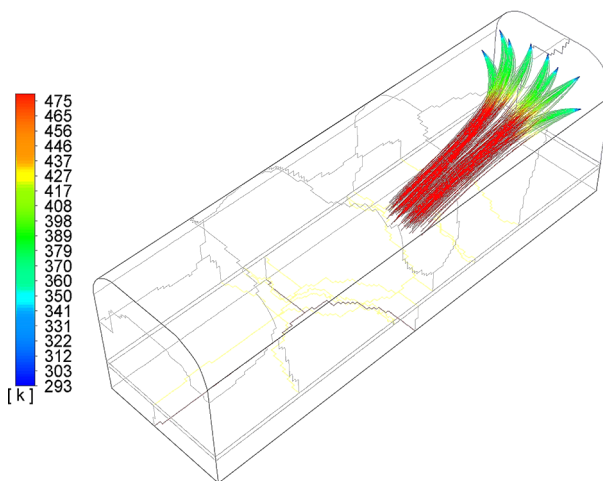


Fig. 12. Temperature of reagent droplets



Fig. 13. Droplet concentration in the longitudinal section of the PRE zone

the PRE zone chamber through lances, are shown in Fig. 14. The initial NO concentration in the exhaust gases is about 2,000 mg/Nm³. After evaporation of moisture from the urea solution droplets, NO is reduced to molecular nitrogen, which is reflected by a decrease in the concentration of nitrogen oxide closer to the rear wall of the PRE zone chamber and the lower layer of particles on the movable grate. The estimated total reduction in nitrogen oxide emissions is about 60 %.

Computer modeling of the SNCR process for the PRE zone chamber in the production of iron ore pellets has sub-

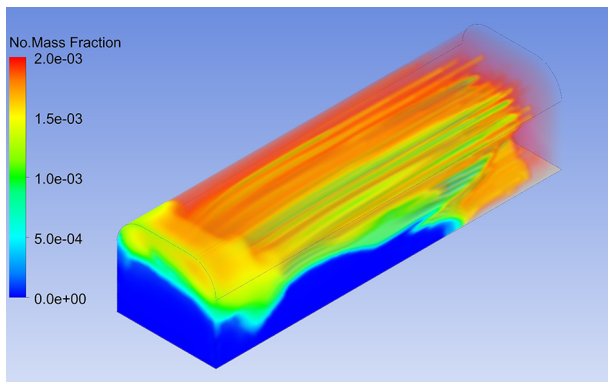


Fig. 14. Nitrogen oxide concentration in the PRE zone with the addition of SNCR reagent

stantiated the possibility of achieving more than 50 % reduction in NO_x emissions when using a 50 % urea solution as a reagent without significant changes in temperature fields.

Conclusions.

1. To reduce the emission of nitrogen oxides during the production of iron ore pellets, the most suitable from a technological and economic point of view is a non-catalytic reduction system, which can be implemented in the preheating chamber (PRE zone) as a zone with optimum temperatures for SNCR, with an expected efficiency of about 50 %.

2. The most commonly used reagents for SNCR are aqueous solutions of ammonia and urea. Given the toxicity of ammonia and its volatile properties, a more acceptable reagent is urea, which is a non-toxic substance and is an emitter of ammonia and amine radical only after the moisture of the droplets evaporates in a high temperature zone.

3. The SNCR process is generally exothermic. Only at the first stage, during the evaporation of moisture droplets and the generation of hydrogen and hydroxyl radicals, there is a consumption of external energy, which is then compensated for by a significant release of energy in the course of the reduction reactions of nitrogen oxides.

4. To model the temperature and hydraulic fields using the ANSYS Fluent software package, a computer model of a preheating chamber (PRE zone) of a movable grate has been created. The reagent is injected through 8 lances with an opening angle of 15° with consumption of 27.36 kg/h (approximately $23.8 \text{ m}^3/\text{h}$) for each.

5. The evaporation process is intense, which accelerates the beginning of urea decomposition and, accordingly, the reduction reaction of nitrogen oxides. The temperature drop in the zone of moisture evaporation does not exceed $10\text{--}25^\circ\text{C}$. The reagent injection (50 % urea solution) with a consumption of 219 kg/h does not significantly affect the temperature regime in the PRE zone, which meets the requirements of the main technological process of pellet production and the required temperature regime for the SNCR process.

6. Modeling the chemical reactions of the SNCR process with the injection of 50 % urea solution droplets into the PRE zone chamber through lances indicates a 60 % reduction in nitrogen oxide emissions.

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Селективне некаталітичне відновлення оксидів азоту на виробництві залізорудних окатків

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Мета. Оцінити за допомогою математичного моделювання можливість упровадження системи селективного некаталітичного відновлення (СНКВ) як заходу зниження викидів оксидів азоту на виробництві залізородних окатків. Визначити особливості використання розчину амоніаку й розчину карбаміду як реагентів процесу СНКВ, вплив введення даних реагентів на температурний режим виробництва окатків та оцінити очікувану ефективність методу СНКВ для очищення відхідних газів від оксидів азоту.

Методика. Результати дослідження отримані при застосуванні CFD-моделювання у програмному забезпеченні ANSYS Fluent. Для моделювання даного процесу побудована розрахункова область, що за розмірами відповідає зоні попереднього нагріву реальної установки виробництва окатків (зона PRE). Для даної області було зроблено дві серії розрахунків: перша без введення реагенту, а друга із введенням розчину карбаміду в якості реагенту системи СНКВ.

Результати. Для першої серії розрахунків були отримані температурне поле та поле тиску в розрахунковій області. Експериментальні дослідження дали можливість стверджувати, що фізичні умови математичної моделі наближені до умов у реальній установці виробництва

окатків. У другій серії розрахунків отримано температурне поле в розрахунковій області та визначено вплив введення реагенту системи СНКВ, а саме зменшення температури в зоні попереднього нагріву установки виробництва окатків на 10–25 °С. Очікувана ефективність відновлення оксидів азоту за допомогою 50 % розчину карбаміду становить близько 60 %.

Наукова новизна. Встановлено, що процес випаровування розчину карбаміду відбувається інтенсивно, що дає змогу прискорити початок розкладання карбаміду й відповідно реакції відновлення оксидів азоту. Падіння температури в зоні випаровування вологи не перевищує 10–25 °С. Уведення реагенту (50 % розчину карбаміду) витратою 219 кг/год суттєво не впливає на температурний режим зони попереднього нагріву. Моделювання хімічних реакцій процесу СНКВ при введенні до камери попереднього нагріву крапель 50 % розчину карбаміду за допомогою фурм показало зниження викидів оксидів азоту на 60 %.

Практична значимість. Упровадження системи СНКВ для установки виробництва окатків забезпечить зниження викидів оксидів азоту, що позитивно вплине на екологічну ситуацію в металургійних регіонах.

Ключові слова: залізородні окатки, селективне некаталітичне відновлення, оксиди азоту, денітрифікація, відхідні гази

The manuscript was submitted 07.06.21.