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PILOT PLANT STUDIES ON NO_x REMOVAL VIA NO OZONATION AND ABSORPTION

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Abstract: The results of experimental investigations on the removal of NO_x from gases applying ozone as the oxidizing agent and the absorption of higher nitrogen oxides in the sodium hydroxide solutions are presented. The experiment was conducted using a pilot plant installation with the air flow rate 200 m³/h, being a prototype of a boiler flue gas duct and a FGD scrubber. It was shown that in the range of $[NO_{ref}] = 50 \div 250$ ppm the mechanism of NO ozonation depends on the molar ratio $X = O_3/NO_{ref}$: for $X \leq 1.0$ oxidation of NO to NO_2 predominates and NO_2 is poorly absorbed, for $X \gg 1.0$ NO_2 undergoes further oxidation to N_2O_5, which is efficiently absorbed in the scrubber. The stoichiometric molar ratio of complete conversion of NO into N_2O_5 is $X = 1.5$, in these studies to reach the effectiveness $\eta \geq 90\%$ the molar ratio X was much higher (2.75).

INTRODUCTION

In Poland, the main sources of air pollution are the following sectors: energy production, industry, transport and municipal sector [11]. The Polish energy generating sector will have to fulfil the EU emission limit values for SO_2, NO_x and dust from coal-fired boilers after January 1st 2016. The new IE Directive [4]has preserved the previous LCP D emission limit values [3], which means that the NO_x emission must be below 200 mg/m³ (O_2 content 6%). Up to now almost exclusively the primary methods of NO_x emission reduction, called low-NO_x combustion systems, were applied in Poland, because they were appropriate to meet the actual emissions limits at reasonable costs [17]. However, the emission limit value 200 mg NO_2/m³ (O_2 content 6%) cannot be executed using only the low-NOx combustion systems in hardcoal-fired and old lignite-fired power plants.

Since the 1980s the emission values for NO_x from coal-fired power plants in the developed EU countries have been controlled by applying the selective catalytic reduction (SCR), which has a status of the Best Available Technology (BAT). The SCR method is very effective in control of the NO_x emission; however its capital and exploitation costs are considered high [12]. The application of SCR in the pulverised coal-fired boilers procures some troubles; the life-time of catalysts is limited because of fly ash erosion

requiring their regeneration or replacement. When biomass is co-fired the catalysts could be poisoned by alkali metals. The use of ammonia or urea may induce risk of the ammonia-slip.

The problems mentioned caused that new technologies (alternative to SCR) have been updated for the highly-efficient and low-cost denitrification of flue gas. Apromising alternative are wet processes for simultaneous removal of NO_x, SO_2 and Hg, which could be combined with the flue gas desulfurization (FGD) methods. Concerning NO_x removal, these methods are based on the preliminary oxidation of low soluble NO and absorption of higher nitrogen oxides in alkaline solutions [6]. Therefore, a lot of effort has been devoted to examine efficient, safe and economic NO oxidizers in recent decades [2]. A considerable amount of works have been done on the ozone injection technology for NO_x control. Despite many publications, patents, economic analyses and promising results in bench-scale in this area there are no commercial applications [7, 15]. The main obstacle is of economic nature; ozone generation is energy-consuming and requires an expensive apparatus, such as powerful ozonizers and feed oxygen supply systems. Therefore, to make the method cost-effective the optimisation of NO ozonation is necessary, which requires further studies.

Most of experimental studies performed on NO ozonation were lab-scale ones with use of bubble washers for the absorption. The authors' team conducted several such experimental studies in previous years [5, 9]. However, the lab-scale conditions are far from conditions existing in industrial installation, like in power plants. The reported studies were conducted in the pilot plant scale(rate flow of carrier gas was 200 m^3/h) in order to examine the influence of such factors, as scale and geometry of the installations and scrubbing of NO_x.

The results of experimental investigations on ability of the NO_x removal from gases applying ozone as the oxidizing agent and a wet scrubber for washing higher nitrogen oxides from the gas are presented. The experiment was conducted using a pilot plant installation with air flow 200 m^3/h, being a prototype of a boiler duct of flue gas and the wet scrubber. The main aim of the research was to confront the effectiveness of NO_x removal obtained in the lab- and pilot- scale and interpretation of the resulted discrepancy.

MECHANISM OF NO OXIDATION BY OZONE

Ozone plays a significant role in the atmospheric chemistry, due to ultraviolet radiation which enhances formation of the hydroxyl radicals OH being the most important cleaning agents in the atmosphere [16]. It also principally contributes to nitrogen oxide NO oxidation into more reactive nitrogen dioxide NO_2, which next undergoes conversion to nitric acid and nitrites removed from the atmosphere with acid rains. Knowledge of the atmospheric chemistry could be helpful in order to understand the mechanism of NO ozonation in the method of NO_x abatement which applies preliminary NO oxidation and absorption of the oxidation products in wet scrubbers. The temperature range is approximately like in troposphere, however lack of ultraviolet radiation causes that the number of chemical reactions is smaller. In order to discuss the assessed experimental results the following set of chemical reactions of major importance was considered (Table 1).

The reaction (1) is very fast, which could lead to a hasty conclusion about the possibility of rapid removal of NO_x in a small oxidizing reactor. The reaction (2) tends to

Table 1. Values of rate constants [18]

Reactions	Values of k_f and k_b (298 K), dm^3, mole, s	No.
$NO + O_3 \rightarrow NO_2 + O_2$	$1.08 \cdot 10^7$	(1)
$NO + NO_2 = N_2O_3$	$4.76 \cdot 10^9 / 3.6 \cdot 10^8$, [14]	(2)
$NO_2 + O_3 \rightarrow NO_3 + O_2$	$2.39 \pm 0.14 \cdot 10^4$	(3)
$NO_2 + NO_3 = N_2O_5$	$3.16 \pm 0.61 \cdot 10^4 / 3.51 \pm 0.71 \cdot 10^{-3}$	(4)
$N_2O_5 + H_2O \rightarrow 2HNO_3$	$2.43 \pm 0.34 \cdot 10^{-3} [H_2O]^{-1}$	(5)
$2O_3 + M \rightarrow 3O_2$	depends on specific M	(6)

be often neglected in the chemical mechanisms of NO ozonation since N_2O_3 is an unstable product. However, N_2O_3 may play an important role in absorption and was therefore included in Table 1 [8].

When the molar ratio of ozone to nitrogen oxide X assumes the sub-stoichiometric values ($X<1$), nitrogen dioxide is the main product of NO oxidation [13]. When the ozone concentration grows to the over-stoichiometric values ($X>1$),the reaction (3) of NO_2 and overdosed O_3 becomes important because NO_3 radicals are formed. For more intensive NO ozonation ($X \gg 1$) nitrogen trioxide reacts with NO_2 to form dinitrogen pentoxide N_2O_5.

The recombination reaction (6) was included into the Table 1 in order to take into account reactions of ozone with particle matter in gas (dust particles), walls and steam, which may influence the necessary ozone excess to achieve the required degree of NO$_x$ emission reduction.

The NO oxidation phase is followed by the absorption phase. It is generally accepted that NO has a very low solubility [10]. The nitrogen dioxide was previously considered to be highly soluble in water [5], which was proven to be a mistake. In fact, NO_2 solubility is low (0.3÷0.5 g/l for p_{NO2} = 0.1 MPa), which is only one order higher than the solubility of NO [10]. The absorbed NO_2 reacts with water producing nitrous and nitric acid [18]:

$$2NO_{2(l)} + H_2O \rightarrow HNO_2 + HNO_3 \qquad (7)$$

Unfortunately, nitrous acid HNO_2 is unstable and can decompose with the release of NO, as follows [19]:

$$3HNO_2 \rightarrow HNO_3 + 2NO + H_2O \qquad (8)$$
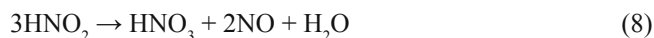
Perhaps, low solubility of NO_2 and the disproportionation of nitrous acid are the reasons why the efficiency of NO$_x$ removal for the molar ratio $X \leq 1$ is not better than 20% [9, 13]. Hence, an intensive ozonation of NO is required to form dinitrogen pentoxide, which can be considered as highly water soluble due to the hydrolysis reaction (5) producing stable nitric oxide HNO_3 [1].

However, the NO_3 and N_2O_5 need a longer reaction time than NO_2, because the reactions (3) and (4) are much slower than the reaction (1). This indicates that NO ozonation has to be much more intensive, and that the residence time must be much longer.

EXPERIMENTAL

The investigations were conducted applying the pilot plant installation (Fig. 1). It included the carrier gas channel 4 of the inner diameter D_i = 290 mm and the length approx. 15 m with the fabric filter 5, after which there was the absorption column 20 of the inner diameter d_i = 190 mm and the height 4 m and the container of sorbent at the bottom 13. The absorber column was equipped with four nozzles injecting sorbent under pressure 0.2 MPa at four levels.

The carrier gas was air sucked into the pilot plant under controlled flow rate (200 m^3/h at the temperature of 20ºC) by the fan 16. The carrier air was doped by nitrogen oxide from the steel cylinder 3 (99,5% of NO from Air Liquide Polska Sp. z o.o.) by the electronic mass flow controller 2 of the type GFC37 (delivered by AALBORG). The concentrations of NO and NO_2 in the carrier air were measured after the absorber demister 22 by the gas analyser 23 Gasmet DX-4000. The reference concentrations NO_{ref} and $NO_{x,ref}$ denoted the concentrations of NO and NO_x which were measured in the carrier air after the absorber when ozone was not generated by the ozonizer 7.

Ozone (1÷5% O_3 in oxygen by volume, depending on the required molar ratio X) was injected into the carrier air under pressure 0.07 MPa by a lance 11 with five nozzles at the rate of 1.2 m^3/h. The oxidizing tubular reactor was approximately horizontal duct connected to the container 13 of sorbent (Fig. 1). The residence time in the tubular reactor was approx. 2 s.

In order to produce ozone the ozone generator 7 of the type OZAT CFS-3 2G from Degremont Technologies Ltd (Ozonia) was fed by oxygen from the steel oxygen cylinder 6. The ozone flow rate was controlled by two rotameters: the main one inside the ozone generator 7 for the measurement of oxygen flow rate and the auxiliary one 9 for the measurement of ozone/oxygen mixture flow rate to the ozone analyser 10 (DMT 964 BT model of BMT MESSTECHNIK GMBH).

The absorbent (aqueous solution of sodium hydroxide)was pumped from the container 13 through four rotameters 14 and atomised in the absorption column 20 by the nozzles 12, 18, 19 and 21.The oxidation-absorption processes were conducted at the temperature of approx. 22°C.

The effectiveness of NO oxidation in the gas phase was determined based on the concentrations of NO measured in the carrier air after the absorber 20 by following expression called the oxidation ratio OR (%):

$$OR = \left(1 - \frac{[NO_{out}]}{[NO_{ref}]}\right) \cdot 100\% \tag{9}$$

The effectiveness of NO_x removal η from the carrier air was defined:

$$\eta = \left(1 - \frac{[NO_{x,out}]}{[NO_{x,ref}]}\right) \cdot 100\% \tag{10}$$

Fig. 1. Scheme of the pilot plant
1 – electronic thermometer (PT-100), 2 – electronic mass flow controller, 3 – steel cylinder of NO,
4 – column, 5 – fabric filter, 6 – steel cylinder of O2, 7 – ozone generator, 8 – valve, 9, 14 – rotameters,
10 – ozone analyser, 11 – ozone lance, 12, 18, 19, 21 – sorbent nozzles, 13 – sorbent container, 15 – pump,
16 – fan, 17 – measuring orifice plate, 20 – absorption column, 22 – demister, 23 – gas analyser

RESULTS

Dynamics of the NO ozonation process

The process of NO ozonation, which comprises several stages due to the different rate constants of the chemical reactions (Table 1), was studied varying the ozone flow rate. The recorded histories of nitrogen oxide and nitrogen dioxide concentrations measured after the absorber 20, when the ozone was started to be injected into the carrier air, for the selected molar ratio $X = 2.0$ are presented in Fig. 2.

The concentration of NO almost immediately reacted to the ozone injection, but the delay time to reach the equilibrium was approximately 1.5 min. The observed time delay was not perhaps of chemical nature. It much rather resulted from long residence time of volume over the surface of sorbent in the container 13 (Fig. 1).The behaviour of nitrogen dioxide was different; after slight delay (approx. 0.2 min.) its concentration grew up to 25 ppm, and after about 1 min. slowly decayed to a fixed value 15 ppm.

The recorded changes of NO and NO_2 concentrations in the carrier air after the absorber 20 when the mole ratio X varied from 0 to 2.75 are shown in Fig. 3. Initially the nitrogen oxide concentration decreased almost proportionally to the ozone molar ratio rise and for approximately $X \cong 1.0$ dropped to 10 ppm. Then, the oxidation rate of the remained NO was slowing down, perhaps because of the competition from much higher concentration of NO_2.

In the first, sub-stoichiometric stage the nitrogen dioxide concentration quickly increased and after achieving the maximum at $X = 1.0 \div 1.25$ it was gradually declining,
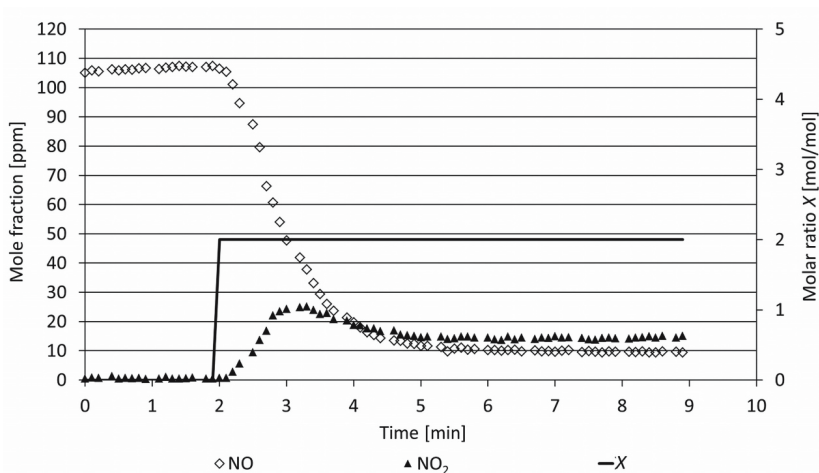
Fig. 2. Changes of NO and NO_2 concentrations after sudden ozone injection into the carrier gas
($X = 2.0$, $[NO_{ref}] = 105$ ppm, $L/G = 10$ dm³/m³, 0.1 M solution of NaOH)
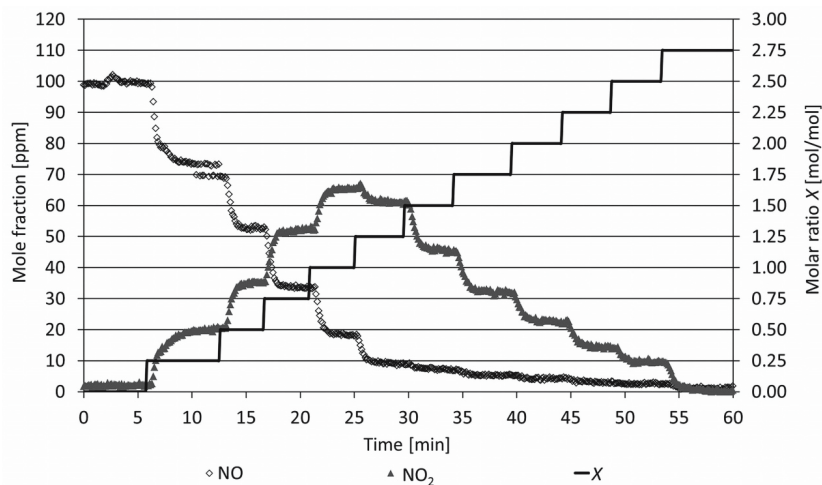
Fig. 3. Time dependence of NO and NO_2 concentrations against the molar ratio
$X = 0 \div 2.75$ ($[NO_{ref}] = 105$ ppm, $L/G = 10$ dm³/m³, 0.1 M solution of NaOH)

and it approached zero at $X \cong 2.75$. An explanation of this behaviour should be related to the chemical kinetics of the NO ozonation: the ozone excess caused oxidation of NO$_2$ to NO$_3$, which reacted with NO$_2$ producing N$_2$O$_5$ according to the chemical reaction (4).

Influence of the molar ratio O_3/NO_{ref} on the effectiveness of NO$_x$ removal

The ozone demand for NO$_x$ removal is an important parameter influencing the cost of flue gas denitrification. It depends not only on the chemistry of NO and NO$_2$ ozonation, but also the mixing pattern of O$_3$ and NO$_x$ and the residence time before the absorption process are important. The role of these physical factors is not yet properly understood, but their unfortunate choice can result in a substantial increase of the ozone excess.

The oxidation ratio OR and the effectiveness of NO$_x$ removal were calculated from the formulas (9) and (10) applying the NO and NO$_2$ concentrations measured in the carrier air after the absorber 20 vs. molar ratio X (Fig. 4). Until the molar ratio X reached approximately 1.0 the oxidation ratio OR was increasing almost proportionally to X in accord with the reaction (1). Further growth of the molar ratio flattened the dependence OR on X, which means that the oxidation rate of the rest of NO declined. The effectiveness of NO$_x$ removal η was low ($< 20\%$) for the sub-stoichiometric ozone flow rate ($X \leq 1.0$), until the ozone flow rate increased substantially ($X \gg 1$) the rate of NO$_x$ removal accelerated and achieved 90%. Hence, due to the different chemical reaction rates the NO ozonation process can be divided into two stages: fast oxidation of NO to NO$_2$ and next much slower reactions (3) and (4) in which N$_2$O$_5$ is finally produced.

Absorption of NO ozonation products: influence of NaOH concentration in aqueous solutions

The influence of the sodium hydroxide concentration in the aqueous solution serving as sorbent in the absorption column 20 on the dependence of the oxidation ratio OR on the molar ratio X is shown in Fig. 5. The effect was not significant, however, the oxidation
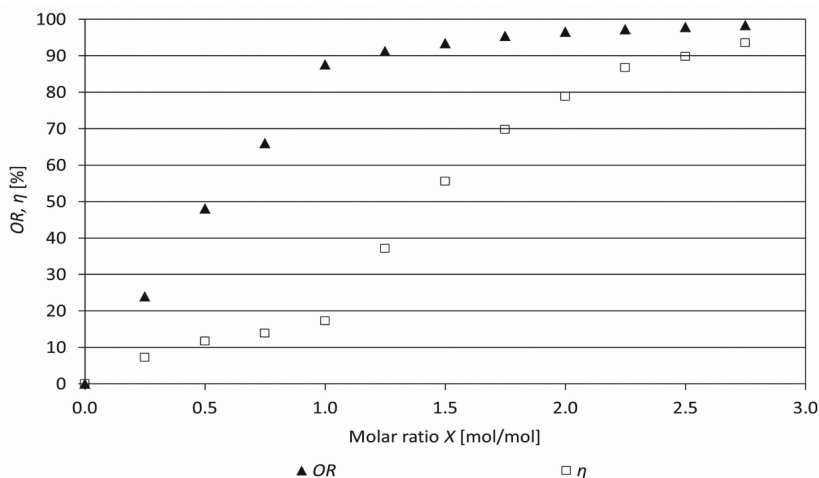
Fig. 4. Oxidation ratio OR and the effectiveness of NO$_x$ removal η vs. molar ratio X ([NO$_{ref}$] = 105 ppm, L/G = 10 dm^3/m^3, 0.1M solution of NaOH)

ratio OR slightly improved when the NaOH concentration increased, especially for the over-stoichiometric conditions ($X > 1.0$). This phenomenon can be explained supposing more efficient absorption of NO_2 in highly alkaline solutions and weaker disproportionate effect [20].

The effect of the NaOH concentration in the solution on the effectiveness of NO_x removal was more interesting (Fig. 6). Approximately, until $X \leq 1$ the influence of the NaOH concentration on the dependence of the effectiveness of NO_x removal η on molar ratio X was insignificant and weakly diverse. This can be explained by almost complete consumption of ozone in the oxidation process of NO and ineffective NO_2 absorption.
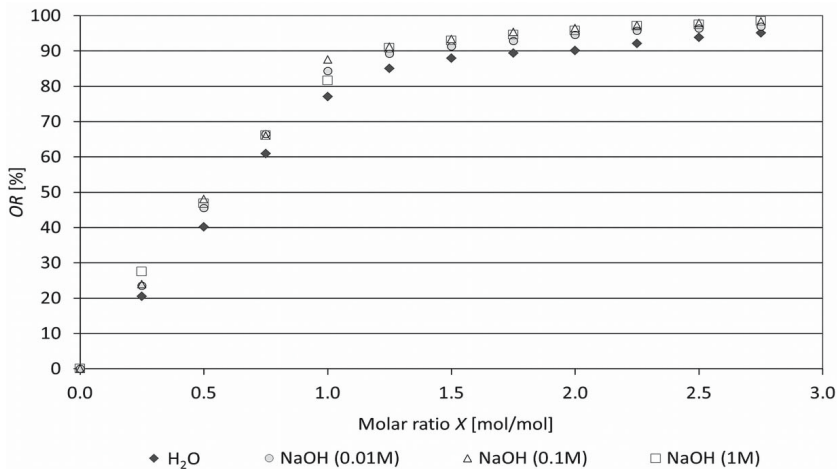
Fig. 5. Oxidation ratio OR vs. the molar ratio X depending on the NaOH concentration
($[NO_{ref}]$ = 100 ppm, L/G=10 dm³/m³)
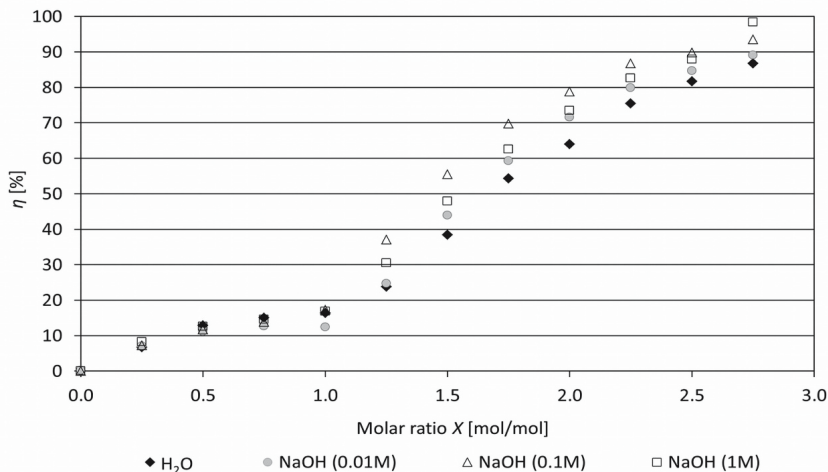
Fig. 6. Effectiveness of NO_x removal η vs. the molar ratio X depending on the NaOH concentration
($[NO_{ref}]$ = 100 ppm, L/G=10 dm³/m³)

Only when $X > 1.0$ the effectiveness of NO$_x$ removal improved for higher concentrations of NaOH; the effect was more explicit, however not dramatic. It is not a surprise that also water appeared to be an effective absorbent [9, 20].

The impact of liquid to the gas ratio (L/G)

The influence of the intensity of sorbent spraying into the carrier air flowing through the absorption column on the oxidation ratio OR for the concentration of NaOH 0.1 M is presented in Fig. 7. The observed effect was very weak in the studied range of $L/G = 0 \div 10$. Because the value $L/G = 0$ means that sorbent was not flowing through the column 26, Fig. 7 indicates that absorption in NaOH solutions does not influence the process of NO oxidation and that the oxidation ratio OR values calculated applying NO measured after the absorption column from the formula (9) are correct.
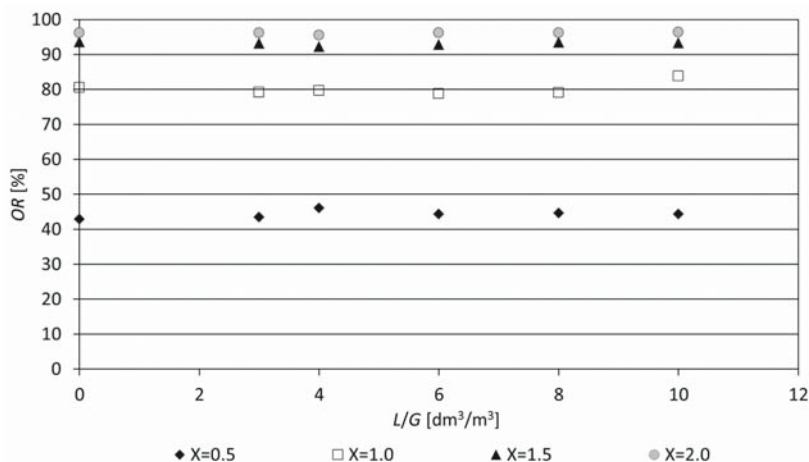

Fig. 7. Oxidation ratio OR vs. the L/G ratio depending on the molar ratio X
([NO$_{ref}$] = 100 ppm, 0.1 M solution of NaOH)

The influence of the intensity of sorbent spraying into the carrier air on NO$_x$ removal was more complicated: for $X = 0.5$ and 1.0 the effectiveness η increased with the L/G ratio and reached approx. 10% plateau for $L/G \geq 4$, whereas for over-stoichiometric X (1.5 and 2.0) the L/G ratio did not affect the effectiveness of NO$_x$ removal (Fig. 8).

The change of the $\eta = f(L/D)$ profile when the molar ratio X switched between sub- and over-stoichiometric valuescan be explained by the consideration of NO oxidation products: for $X \leq 1.0$ the main oxidation product was NO$_2$ and the increase of sorbent flow improved the effectiveness for small L/G (< 4). For the over-stoichiometric X (1.5 and 2.0) perhaps the NO ozonization products were predominated by N$_2$O$_5$ and NO$_2$ disappeared from the carrier air. This also explains high effectiveness of NO$_x$ removal even without scrubbing ($L/G = 0$) (Fig. 8).

Influence of the initial concentration of NO$_{ref}$

The effect of the initial concentration of nitrogen oxide NO$_{ref}$ on its oxidation rate was investigated by changing NO$_{ref}$ in the carrier air and adjusting the ozone concentration in
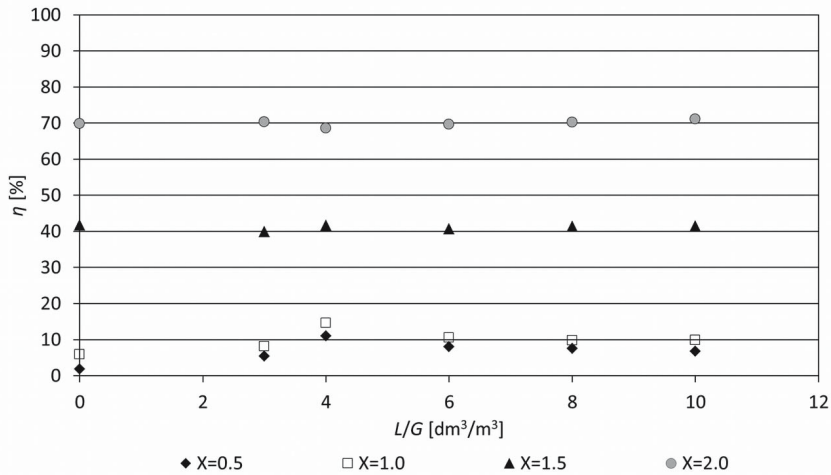
Fig. 8. Effectiveness of NO$_x$ removal η vs. the L/G ratio depending on the molar ratio X
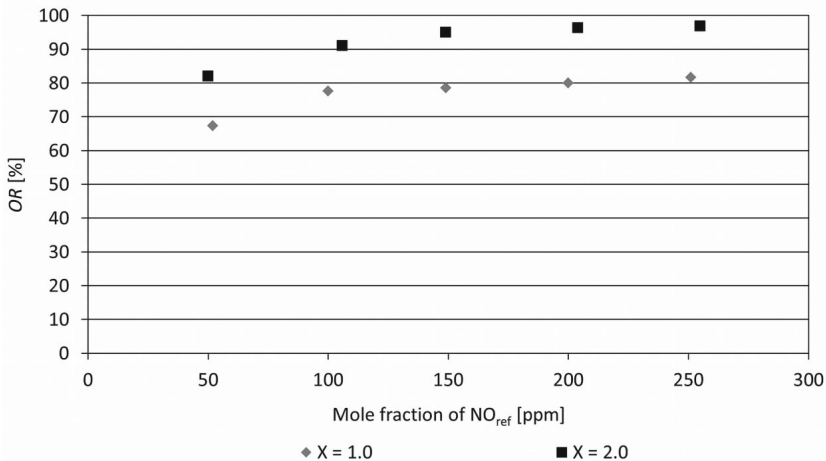([NO$_{ref}$] = 100 ppm, 0.1 M solution of NaOH)

Fig. 9. Oxidation ratio OR vs. the reference concentration NO$_{ref}$ at the molar ratios X = 1.0 and 2.0
(L/G = 10 dm³/m³, 0.1 M solution of NaOH)

oxygen supplied by the ozone generator 7 to assure the molar ratio X = 1.0 or 2.0. In such a way the conditions of mixing ozone and nitric oxide remained unchanged.

Fig. 9 shows that the decrease of NO$_{ref}$ concentration had a similar impact on the oxidation process of NO for the molar ratios X = 1.0 and 2.0; the oxidation ratio OR diminished with the decrease of NO concentration.

The same effect was observed for the removal of NO$_x$; the effectiveness η diminished with the decrease of NO concentration below 150 ppm (Fig. 10). In this case the impact appeared to be even stronger.
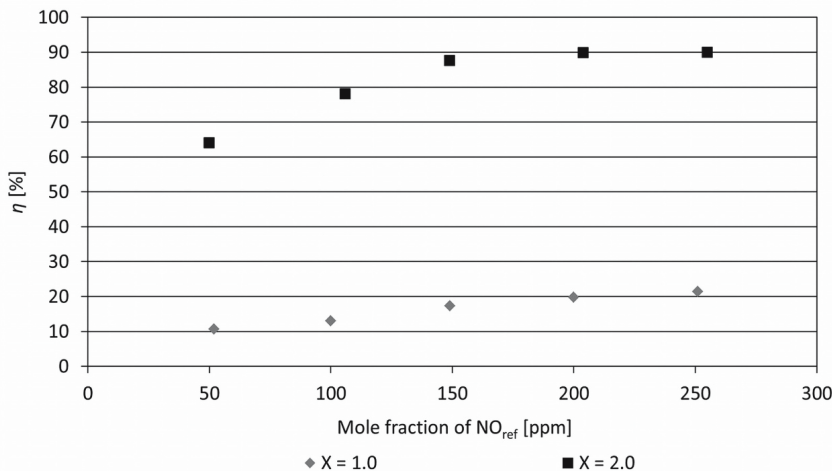
Fig. 10. Effectiveness of NO$_x$ removal η vs. the reference concentration NO$_{ref}$ for the molar ratios
$X = 1.0$ and 2.0 ($L/G = 10$ dm^3/m^3, 0.1 M solution of NaOH)

The fall of the effectiveness of NO$_x$ removal can be an effect of diminished rates of the chemical reactions (1), (3), and (4) and abated efficiency of the oxidation products scrubbing for the diminished NO$_{ref}$ concentrations below 150 ppm.

DISCUSSION

The obtained results are qualitatively similar to the results of the previous lab-scale experimental studies, when the oxidation products of NO were absorbed in bubble washers [5]. This time it was seen even more distinctly that for [NO$_{ref}$] $\cong$ 100 ppm the process of NO ozonation can be divided into two stages depending on the molar ratio X values. For the sub-stoichiometric values ($X \leq 1.0$) the oxidation of NO to NO$_2$was the predominating process and the oxidation ratio OR reached approx. 90%. The concentration of NO$_2$ rose, because its absorption was inefficient and the consumption rate by the reaction (3) was small (Fig. 3). The effectiveness of NO$_x$ removal was below 20%. In the second stage ($X > 1.0$) the overdosed ozone oxidized NO$_2$ which led to dinitrogen pentoxide formation and improvement of the effectiveness of NO$_x$ removal above 90%.

There are some quantitative differences between the results obtained in the lab- and pilot scale studies [5]. The scale effect in the NO oxidation process was not substantial; the oxidation ratio OR achieved 90% in the pilot scale installation, while in lab-scale it was 95% for $X = 1.0$. This difference can be explained by more difficult conditions of ozone and NO mixing in the much larger pilot-scale duct.

The scale effect was more evident for the effectiveness of NO$_x$ removal. In the lab-scale studies the effectiveness η exceeded 90% for the molar ratio $X = 1.5$, whereas in the pilot plant studies to reach such value of the effectiveness η the ozone excess had to increase up to $X = 2.75$ (Fig. 4). This substantial discrepancy can be explained taking into consideration the fact that N$_2$O$_5$ at the room temperature forms aerosol, whose particles were more effectively precipitated in a bubble washer than in the scrubber.

The significance of the molar ratio value $X = 1.5$ can be explained by assumption that the conversion of NO_2 into N_2O_5 is a necessary condition for the efficient removal of NO_x. A combination of the chemical equations (1), (3) and (4) leads to the summary chemical reaction:

$$NO + 3/2O_3 = 1/2N_2O_5 + 3/2O_2 \tag{11}$$
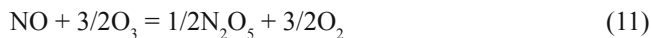
It means that the stoichiometric molar ratio O_3/NO should be $X = 1.5$, which is 50% more than it results from the model of fast oxidation of NO by ozone in the Eq. (1).

CONCLUSIONS

The results of the conducted experimental studies on the removal of NO_x ($[NO_{x,ref}]$ = 50÷250 ppm) from the carrier air applying NO ozonation and the oxidation products scrubbing lead to the following conclusions:

1. The mechanism of NO_x removal from gases by the method of NO ozonation and absorption depends on the molar ratio $X = O_3/NO_{ref}$: for $X \leq 1.0$ the oxidation of NO to NO_2 is the predominating reaction and NO_2 is poorly absorbed, for $X \gg 1.0$ NO_2 undergoes further conversion in reactions (3) and (4) and the absorption of the oxidation products becomes effective.
2. The effectiveness of NO_x removal appeared to be sensitive to the installation scale; its increase results in a higher demand of ozone supply.
3. The concentration of NaOH in aqueous solutions had a small impact on the effectiveness of NO_x removal from gas and lack of sorbent injection only slightly decreases the effectiveness η.
4. The effectiveness of NO_x removal was distinctly reduced when the initial concentration of NO_{ref} diminished below 150 ppm.

SYMBOLS

d absorption column diameter, mm
D carrier gas channel diameter, mm
k reaction rate constant, dm^3, mol, s
L/G liquid to gas ratio, dm^3/m^3
$[NO_x]$ mole fractions of NO_x, ppm
$[NO]$ NO mole fraction, ppm
$[NO_2]$ NO_2 mole fraction, ppm
OR oxidation ratio of NO in the gas phase, %
X molar ratio of O_3 to NO, mol/mol
η effectiveness of NO_x removal, %

Subscripts
b backward
f forward
i inner
out   output

ref   reference
l   in liquid

ACKNOWLEDGEMENTS

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BADANIA W SKALI PILOTOWEJ DOTYCZĄCE EFEKTYWNOŚCI USUWANA NOx PORZEZ UTLENIANIE NO I ABSORPCJĘ

Przedstawiono wyniki badań doświadczalnych dotyczące usuwania NO_x z gazów z zastosowaniem ozonu jako utleniacza i absorpcji wyższych tlenków azotu w roztworach wodorotlenku sodu. Badania prowadzono na strumieniu powietrza 200 m^3/h w instalacji pilotowej będącej prototypem instalacji kotłowej odprowadzenia spalin i skrubera IOS. Wykazano, że w zakresie $[NO_{ref}]$ =50÷250 ppm mechanizm ozonizacji NO zależy od stosunku molowego $X = O_3/NO_{ref}$: dla $X \leq 1.0$ przeważa utlenianie NO do NO_2 a NO_2 jest słabo absorbowany, dla $X \gg 1,0$ NO_2 ulega dalszemu utlenianiu do N_2O_5, który jest efektywnie absorbowany w skruberze. Stosunek molowy przy całkowitej konwersji NO do N_2O_5 wynosi $X = 1.5$, w przeprowadzonych badaniach, aby osiągnąć efektywność $\eta \geq 90\%$ stosunek X był dużo większy (2,75).