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Using Hydroponic Biomass to Regulate NO_x Emissions in Long Range Space Travel

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Abstract

The incineration of wastes is one of the most promising reclamation technologies being developed for life support in long range space travel. However, incineration in a closed environment will build up hazardous NO_x if not regulated. A technology that can remove NO_x under microgravity conditions without the need of expendables is required.

Activated carbon prepared from inedible wheat straw and sweet potato stalk that were grown under hydroponic conditions has been demonstrated to be able to adsorb NO and reduce it to N₂. The high mineral content in the activated carbon prepared from hydroponic biomass prohibits high surface area production and results in inferior NO adsorption capacity. The removal of mineral from the carbon circumvents the aforementioned negative effect. The optimal production conditions to obtain maximum yield and surface area for the activated carbon have been determined.

A parametric study on the NO removal efficiency by the activated carbon has been done. The presence of oxygen in flue gas is essential for effective adsorption of NO by the activated carbon. On the contrary, water vapor inhibits the adsorption efficiency of NO. The NO adsorption capacity and the duration before it exceeds the Space Maximum Allowable Concentration were determined.

After the adsorption of NO, the activated carbon can be regenerated for reuse by heating the carbon bed under anaerobic conditions to above 500°C, when the adsorbed NO is reduced to N₂. The regenerated activated carbon exhibits improved NO adsorption efficiency. However, regeneration had burned off a small percentage of the activated carbon.

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Introduction

Life support systems are what make human travel a possibility. In long range space travels, such as the travel to Mars, life support cannot depend upon storage alone, it requires a fully regenerative system as well, i.e. waste must be reclaimed for reuse.

Steam reformation, supercritical water oxidation, electrochemical oxidation, and incineration are a few of the solid waste reclamation technologies that are being developed and tested for use in space travel(1). Currently though, it seems that incineration might be the best choice among the previously mentioned, in providing a fully regenerative system. Through rapid conversion, incineration of the inedible parts of wastes and crops produces carbon dioxide, water, and minerals. Incineration is already the most thoroughly developed technology for use in a terrestrial environment. However, with the use of incineration in a closed environment, there is the eventual buildup of pollutants that are emitted in the process. The resulting NO_x and SO₂ pollutants need to be removed and recovered for reuse by a flue gas cleanup system.

Important things to consider when developing a flue gas clean up technology for use in long range space travels are safety, energy requirements, sustainability, and doable under a microgravity condition. Due to the sensitivity and restrictions of space missions, a flue gas clean up system lacking in any of these considerations can be hazardous and could potentially compromise the missions. Technologies requiring things such as expendables or the use of catalysts (2-4) are unsuitable for space missions due to the loss of valuable resources and the possibility of catalyst poisoning thus limiting the life-span of a catalyst. Also, due to the microgravity, it is difficult to use wet processes (5-14) that handle liquids, such as spray absorbers. Consequently, even though there are numerous flue gas clean up technologies developed (15-23), taking into consideration the limitation each provides, the number of reliable and applicable systems seem to be dwindling.

Commercial activated carbon, made mostly from materials such as coconut shells and coal, has been studied for the adsorption and/or reduction of NO_x and SO₂ (24-28). In this paper, we study the use of the activated carbon prepared from hydroponic grown wheat straw and sweet potato stem for the control of air pollutants that are a result of incineration during space travel. Both wheat straw and sweet potato stalk are inedible biomass that can be continuously produced in the space vehicle.

It was found that there is actually a minuscule amount of SO₂ in the flue gas from the incineration of hydroponic biomass, and that most of the sulfur from the biomass ends up as sulfate in flyash. Since SO₂ should have already reacted with the alkali metal, the technique entails the carbonization of the wheat straw and sweet potato stalk, resulting in an activated carbon for the adsorption of NO_x and then a reduction of the adsorbed NO_x by carbon to form N₂. Since most NO_x in flue gas from combustion is in the form of NO, and NO₂ is readily adsorbed on the activated carbon(29-30), this paper concentrates on the removal of NO. Parametric studies on the production of activated carbon and the

adsorption of NO by the carbon have been conducted. The optimal conditions and effectiveness of this procedure to regulate NO emissions have been determined.

Experimental Section

Apparatus. A schematic diagram of the experimental set-up is shown in Fig.1, which was used for the preparation of char from inedible biomass, the adsorption of NO_x on a char bed and the reduction of NO_x by carbon at high temperatures to form N₂. The main component of the system is a 2" I.D. (for the preparation of char) or 3/4" I.D. (for the adsorption, de-adsorption and regeneration) stainless steel tube (all 30" in length) reactor. The tubular reactors were placed inside a furnace (Thermolyne, Type F121100) for heating. The furnace has the function of running an automatic set point ramping program.

Materials. The following materials were used: NO (5% with N₂ as balance, Scott Co.), standard NO (500ppm with N₂ as balance, Scott Co.), CO₂, N₂, O₂ (Airgas Co.) hydroponic grown wheat straw (WS) and sweet potato stalk (SP).

Preparation of Carbon. Wheat straw and sweet potato stalk were cut into about half to one inch pieces using a blender. After the biomass was shredded, it was packed tightly into a stainless cylinder for pyrolysis and activation. Nitrogen and Carbon dioxide were used as the pyrolysis and activation gases, respectively. The gas flow rate for pyrolysis was 0.5-1.0L nitrogen per minute and activation was 0.25L carbon dioxide per minute. The amount of biomass used was approximately 50.0-60.0g for each batch. Pyrolysis and activation temperature (between 300°C and 850°C) and times (between 0.5 hr and 6 hr) were varied during carbonization in order to determine optimal activation conditions. The activation temperature was 50°C higher than the pyrolysis temperature. The notation of the activated carbon "WS-2-600-1-650" and "SP-2-600-1-650" indicate that the activated carbon was prepared from wheat straw and sweet potato stalk, respectively with a 2 hrs pyrolysis time at 600°C followed by 1 hr of activation at 650°C. Once activation was complete, CO₂ was supplied to the sample until it could be sealed in a container.

Biomass on a space mission would likely come from a hydroponic system. The total mineral content of hydroponic biomass can be much higher than field-grown biomass if nutrients are supplied luxuriously to the hydroponic solution. A typical hydroponic plant solution(31-32) has a nutrient ratio of N:K:Ca:P:S:Mg =16:6:4:2:1:1 and contains micronutrients of B, Mn, Zn, Cu, Co, Mo, and Fe. The concentration of potassium (K) in the solution is about 6 mM. Thus, hydroponic activated carbon adsorption efficiencies may differ significantly from field-grown biomass. Field grown biomass generally has less than 10% mineral (ash) content, while hydroponic biomass can have as much as 30% mineral content. Because of this, many of the experiments were performed using char, which had been soaked in deionized water (for 2 hours) to remove the soluble minerals. After soaking, the char was drained and dried at 200°C for one hour before use.

Characterization. Specific surface areas of samples were determined by gas adsorption. An automated adsorption apparatus (Micromeritics, ASAP 2010) was employed for these measurements. Nitrogen adsorption/desorption was measured isothermally at -196°C . Before any such analysis, the sample was degassed at 250°C in a vacuum at about 10^{-3} torr. The nitrogen isotherms were analyzed by the BET equation, to determine the surface areas of the chars. BJH adsorption cumulative surface areas of pores of the samples also were determined.

Adsorption. Most of NO_x in flue gas from combustion is in the form of NO . Also, NO_2 is readily adsorbed on the activated carbon. Consequently, efforts were directed to determine conditions for maximal removal efficiency of NO . Adsorption efficiency of NO on the activated carbon was studied to evaluate the effects of temperature, oxygen composition, moisture and flow rate on the production of effective activated carbon.

The adsorption experiments were performed by using a simulate flue gas with variable concentrations of N_2 , carbon dioxide, oxygen, NO and H_2O . NO and NO_2 concentrations were analyzed by a chemiluminescent NO_x analyzer (Thermo Environmental Instruments Inc., model 14A). The amount of NO_x absorbed by the activated carbon was determined from the difference in NO_x concentration of the inlet and outlet gases. It was assumed that missing NO_x was adsorbed by the activated carbon.

Reduction and Regeneration. Reduction of NO and regeneration of the activated carbon were performed by heating the NO loaded char in the absence of oxygen. In order to evaluate the behavior of the process, a purge gas flow of nitrogen was applied during experiments, while the outlet gas was directed to an analyzer. The sample was heated from room temperature to 600°C at a rate of $40^{\circ}\text{C}/\text{min}$. The gas flow rate for reduction and regeneration was 1.0 liter nitrogen per minute.

Space Maximum Allowable Concentration. The space maximum allowable concentration (SMAC) of NO in a human occupied cabin is 4.8 ppm, and thus reduced NO concentrations to the level of SMAC can serve as an indicator for meeting the requirement. Experiments were conducted at room temperature using sweet potato activated carbon before (SP-2-600-1-650) and after (SP-2-600-1-650(SD)) soaking and drying. The principle variables manipulated were inlet of oxygen concentration and the ratio of weight to flow rate, W/F , (W : weight of the activated carbon in g. and F : flow rate of flue gas in L/min) in order to determine the conditions to keep outlet NO concentrations below SMAC. Inlet gas concentrations were controlled by varying gas flow rates. Oxygen concentration ranged from 5% to 15% and W/F ranged from 15 to 60 $\text{g}\cdot\text{min}/\text{L}$.

Results and Discussion

Preparation and Characterization of Activated Carbon

Burnoff. Preparation of activated carbon was conducted by heating hydroponic grown wheat straw and sweet potato stalk under anaerobic conditions. Nitrogen and carbon dioxide were used as the pyrolysis and activating gases, respectively. Time and

temperature were varied during pyrolysis and activation to determine optimal carbonization conditions.

In order to determine optimal carbonization temperatures, samples of wheat straw and sweet potato stalk were heated at 100°C intervals between 300 to 800°C for two hours during pyrolysis and between 350°C to 850°C for one hour during activation. Afterwards, percent burnoff was measured. Higher carbonization temperatures caused larger portions of the samples to burn off, as shown in Fig.2. The burnoff was 68% at 600°C and 86% at 800°C for wheat straw, while 66% at 600°C and 92% at 800°C for sweet potato stalk. Both samples appear to follow the same burnoff trend, the percent burnoff increases only slightly with the increase of temperature between 400°C to 600°C. However, pyrolysis and activation temperatures above 700°C were observed to cause significant amounts of wheat straw and sweet potato stalk to burn to ash. It is thus not recommended that reactions be run at temperatures exceeding 600°C.

Surface Area and Cumulative Pore Area. The activated carbons were characterized by the measurement of their average pore size and surface area. There are three types of pores which can develop in the carbon particles: micropores (<2nm), mesopores (2-50nm) and macropores (>50nm). BET surface area of wheat straw char carbonized at temperatures between 300°C and 700°C is shown in Fig.3. The surface area passes through a maximum of 105.2 m²/g at a pyrolysis and activation temperature of 600°C and 650°C respectively. The BET surface area of sweet potato stalk exhibits similar behaviors as that of wheat straw, being 88.1 m²/g, 84.7 m²/g, and 132 m²/g at a pyrolysis temperature of 300°C, 400°C, and 600°C, respectively. The decrease in surface area beyond 600°C is caused by sample burning off. Using temperatures much lower than 600°C would compromise the maximum amount of effective adsorption surface area attainable (Fig. 3). It is not only important to run reactions at temperatures low enough to prevent burnoff and ash formation but also high enough to generate effective surface areas, which would be at 600°C for wheat straw.

Fig.4 shows the BJH adsorption cumulative pore area of wheat straw activated carbon generated at different pyrolysis and activation times. It is evident from the plot that samples derived from longer pyrolysis and carbonization times exhibited a higher micropore count compared to shorter times. As with temperature generation optimum, however, too long pyrolysis and activation reaction times cause an adverse increase in burnoff percentage. Though wheat straw carbonized with a pyrolysis time of six hours and activation time of 2 hours still demonstrated a higher cumulative pore area than the shorter times, it also produces larger amounts of burnoff. Since reaction temperatures were kept below 600°C, ash formation that would have diluted effective surface area was prevented. Even though ash does not form, pyrolysis and activation times must still be chosen to create a balance between pore formation and burnoff, one that would generate a high micropore count but at the same time, minimize material loss. The optimal pyrolysis and activation times for wheat straw are 2 hours and 1 hour respectively.

Determining Optimal Temperature and Time for Carbon Preparation. Optimal pyrolysis and activation temperatures and times for carbon preparation were determined

based on the amount of NO_x that can be adsorbed by the activated carbon. The adsorption capacities of wheat straw activated carbons generated by different pyrolysis and activation temperatures are shown in Fig.5. A gas mixture containing 250ppm of NO, 5% O₂, 10% CO₂, with N₂ as the balance was passed, at a flow rate of 250ml/min, through a tubular reactor containing 2g of activation carbon (W/F=8g.min.L⁻¹) at 25°C. It is evident from the plots that the WS-2-600-1-650 activated carbon had the best adsorption efficiency. Samples carbonized above 600°C have higher ash concentrations than those carbonized below, while those carbonized below have lower percent micropore counts and surface area—both explaining why wheat straw generated at 600°C had the best adsorption efficiency.

The NO adsorption efficiencies of wheat straw samples carbonized by differing pyrolysis and activation times are shown in Figure 6. It is evident from the plots that activated carbons carbonized by prolonged pyrolysis and activation times have better adsorption efficiencies than those carbonized by shorter times due to higher pore count and BET surface area. The micropore count and the surface area of activated carbon increases with an increase of the preparation time, which explains why the samples with the longest pyrolysis and activation times have the best adsorption efficiencies. However, prolong activation results in more burnoff and the production of ash. A balance must be reached when setting reaction parameters, one that will generate the largest surface area without a significant burnoff. We have found that the optimal pyrolysis and activation times for wheat straw are two and one hour, respectively.

The hydroponic biomass possesses high mineral content. The effect of the minerals on the activated carbon on NO adsorption efficiency was studied. The activated carbon was first soaked in water to dissolve the soluble minerals and then dried to remove the moisture from the carbon particles. The adsorption experiments using the mineral-free activated carbon were performed and the results indicate that the NO adsorption efficiency was substantially improved (Fig. 7 and 8). A 100% NO removal efficiency was obtained for the entire 2 hr experiment, using a gas mixture containing 250 ppm NO and 10% O₂ and at a W/F of 30g.min.L⁻¹. The improved NO removal efficiency by the activated carbon with mineral removed is attributed to the increase of the carbon surface area, which was otherwise covered by the minerals. Because of this finding, the parametric study on the NO removal efficiency was performed mostly with the activated carbon having mineral content removed by water dissolution.

Parametric Study of the Removal Efficiency of NO

Oxygen Effects on Adsorption. Experiments on the effect of oxygen on NO adsorption by two activated carbons, SP-2-600-1-650 and WS-2-600-1-650 have been performed. The soluble minerals in both of the activated carbon have been removed. Oxygen concentrations were varied between 0 and 10%. As Fig.9 (SP-2-600-1-650) and Fig.10 (WS-2-600-1-650) show, the NO adsorption on both activated carbons increases with the increase of oxygen concentration in flue gas. A 100% NO removal efficiency was obtained with an oxygen concentration of 10% and with a W/F of 30g.min.L⁻¹ during 2 hours adsorption. It is obvious that the presence of oxygen is critical for the NO

adsorption by carbon to be effective. This phenomenon is attributed to the catalytic oxidation of NO by O₂ on the carbon surface to form NO₂, which is more readily adsorbed by the activated carbon.

Moisture Effects on Adsorption. It is expected that the high temperature flue gas will be cooled down before passing to the carbon bed to avoid the combustion of carbon due to the presence of flue gas oxygen. This cooling down results in the condensation of water vapor. Flue gas can contain up to 3.0 % v/v H₂O even after cooling down to room temperature, thus it is important to study the effect of water vapor on the removal efficiency of NO by carbon. Fig. 11 (SP-2-600-1-650) and Fig.12 (WS-2-600-1-650) show that moisture causes a significant decrease in NO removal efficiency by carbon. The more water vapor present in the flue gas, the lower the NO removal efficiency exhibited. This is due to the fact that water vapor competes effectively with NO for the adsorption sites on carbon particles. The detrimental effect of water vapor on NO adsorption can be overcome by the removal of water vapor either by drying agents or by cooling flue gas to low temperatures prior to adsorption.

Reduction of NO by the Activated Carbon

The adsorbed NO can be desorbed from the activated carbon if temperature of the carbon bed is raised. Further increases of temperature results in the reduction of NO by activated carbon to produce N₂. Simultaneously, the activated carbon is regenerated as a result of the reduction of NO to N₂(27).

Experiments on the reduction of the adsorbed NO by the activated carbon were performed by heating the NO saturated carbon under anaerobic conditions. In order to evaluate the behavior of the process over time, a purge gas flow of 1.0 L/min N₂ was passed through the carbon bed and subsequently directed to the NO_x analyzer. Desorption was conducted with a temperature ramp rate of 40°C/min from room temperature to 600°C. As the temperature of the carbon bed was increased, NO was desorbed from the surface of the activated carbon. Further increase of the temperature results in the reduction of NO by the activated carbon to N₂. The fraction of the adsorbed NO that is reduced to N₂ can be calculated by subtracting the NO coming out of the carbon bed from the total amount of NO adsorbed. The fraction of the adsorbed NO that is reduced depends on the temperature and the flow rate of N₂ gas.

Fig.13 shows the fraction of the desorbed NO integrated over the temperatures as the temperatures of the carbon bed was raised. As can be seen, the fraction of the total NO desorbed as NO was less than 100% of the total NO adsorbed, 38.5% and 9.1% for sweet potato and wheat straw activated carbons, respectively. The difference of which is attributed to the reaction of NO with the activated carbon to form N₂. From the desorption curve as a function of temperature, the NO desorption mainly took place at temperature below 450°C, while the NO reduction by carbon occurred at temperature above 450°C, the higher the temperature the more effective the reduction is.

Another set of experiments were performed to study the reduction of NO by activated carbon as a function of temperature and W/F, the ratio of the amount of carbon to flow rate of N₂. In this study, temperatures were varied between 300 and 500°C and W/F between 10 and 40 g.min/L. Fig.14 shows that, in the case of the sweet potato activated carbon, 100% of NO was reduced to N₂ at 500°C with a W/F above 10 g.min./L, while at 450°C it would require a W/F above 30 g.min./L. For wheat straw activated carbon, NO can be reduced to N₂ at lower temperatures and smaller W/F ratios than those of sweet potato (Fig. 15). All inlet NO was reduced to N₂ at 450°C with a W/F above 15g.min.L⁻¹. Higher temperatures or larger W/F ratios are favorable for NO reduction.

The NO reduction efficiency also depends on the concentration of NO in the system. Fig. 16 shows NO reduction by sweet potato and wheat straw activated carbons at 450C with two inlet NO concentrations, 250 ppm and 1000 ppm. The results indicate that the higher the inlet NO concentrations, the smaller the fraction of the inlet NO is reduced at a given W/F. All of inlet NO was not reduced to N₂ by the sweet potato activated carbon until the W/F reached 30 g.min/L and 40 g.min/L for 250 ppm and 1000ppm of inlet NO respectively. The activated carbon made from wheat straw can reduce NO more effectively than that from sweet potato. The entire inlet NO was reduced by the wheat straw activated carbon with a W/F of only 15 g.min/L and 30 g.min/L for 250ppm and 1000ppm of NO, respectively.

Space Maximum Allowable Concentration (SMAC) of NO

The space maximum allowable concentration (SMAC) of NO in a human occupied cabin is 4.8ppm. Experiments were conducted to determine conditions for NO adsorption on SP-2-600-1-650 at room temperature such that the NO concentration exiting the carbon bed is less than 4.8ppm. The activated carbons before and after the removal of minerals with water dissolution were both examined. The parameters studied included inlet oxygen concentration (5% to 15%), and carbon weight to flue gas flow rate ratio (W/F: 15 to 60 g.min./L). The time that the carbon bed can hold before the NO_x concentration exiting the bed exceeds the SMAC will be called SMAC time.

Fig.17 and 18 show that the SMAC time for both activated carbons increase with the increase of W/F and oxygen concentrations. The removal of minerals from the activated carbon increases the surface areas and results in a much longer SMAC time. The SMAC time was 22 min., 30 min., 36 min., and 62 min. with a W/F of 45 g.min/L when flue gas contains 5%, 8%, 10%, and 15% O₂, respectively using the activated carbon containing mineral. However, the SMAC time was substantially increased to 145 min, 215 min, 330 min, and 500 min at a W/F of 45 g.min/L with flue gas containing 5%, 8%, 10%, and 15% O₂ using the activated carbon with mineral removed.

Experiments were conducted to determine the effects of the regeneration on activated carbon in terms of NO removal efficiency, as assessed by the carbon's SMAC time. The results indicate that regeneration improves the removal efficiency of NO. This phenomenon is attributed to the increase of surface area and micropores of the activated carbon. However, it was observed that additional carbon burns off occurs during

regeneration, which causes the overall amount of activated carbon to decrease after each regeneration cycle. The loss of mass were determined to be about 0.99% for wheat straw and 0.49% for sweet potato stalk activated carbon per cycle of regeneration at 600°C.

Assessment of the Amount of Inedible Biomass Required

Lastly, due to the extent of the mission, the sufficiency of the amount of inedible biomass in providing the activated carbon for the life support systems should be assessed. With a six person crew, such as the mission planned for Mars, the average food consumption is about 0.25kg/d per capita (33-34). Six people would need 1.5kg of wheat per day. Wheat straw yield depends on the specific varieties harvested and is widely affected by agronomic and climatic factors. An average ratio of 1.3 kg of straw per kg of grain is found for most common varieties (35). Burnoff accounts for about 66.7% at 600°C in pyrolysis and 650°C in activation, while the loss of carbon mass from soaking and drying was determined to be about 14.4%. So as a result, 203kg of wheat straw activated carbon can be produced per year.

By incinerating feces, inedible biomass and trash, between 3g and 30 g of NO_x can be produced per day, depending mostly on the amount of nitrogen in the inedible biomass. The range in the amount of NO_x produced covers 90% pre-treatment removal of nitrogen to no pretreatment (36). (Calculations were made assuming 30g. NO emission). About 10% of nitrogen in the waste forms NO_x (37).

Regeneration of the adsorbing activated carbon shall occur once a week via the reduction reaction. The loss of carbon mass was determined to be about 0.99% at 600°C per cycle of regeneration, After one year, all the activated carbon should be incinerated and replaced. Calculations based on the above assumptions yield 210g NO emissions per week, and the adsorption capacity of NO by the activated carbon is 5.46mg/g carbon, which will need at least 38.5kg of wheat straw activated carbon all year long. These can be distributed among one adsorption tank, just with a load of 64.6kg of wheat carbon in the beginning of the year. Every week, the tank should be regenerated. After one year, the total loss of carbon would be 26.1kg, taking into consideration 52 cycles of regeneration. In the end of the year, there will still be 38.5kg carbon to maintain high adsorption efficiency. So the activated carbon produced from wheat straw is enough to control NO_x emission. In fact, the activated carbon can be regenerated many times with the same material, while adsorption tends to improve rather than degrade (38).

Conclusion

We have demonstrated that wheat straw and sweet potato stalk, inedible by-products of crop that may be grown in space vehicles, can be converted to the activated carbon for the adsorption and reduction of NO in an effective manner. No expendable material, such as binders, is needed for making an effective activated carbon.

The optimal carbonization temperature of wheat straw and sweet potato was both found to be around 600°C when the burnoff was 65 %. The BET surface area of the wheat straw activated carbon with high mineral content was 105.2 m²/g, while the surface area reached 300 m²/g after the mineral was removed by water dissolution. Higher

carbonization temperatures caused larger portions of the biomass to burn off and turn to ash.

The presence of oxygen in flue gas is necessary for an effective adsorption of NO by the activated carbon. On the contrary, water vapor inhibits the adsorption efficiency of NO. Consequently, water vapor in flue gas should be removed either by condensation at low temperatures or by drying agents before adsorption to ensure high NO adsorption efficiency. All of NO in the flue gas was removed for more than two hours when 10% oxygen was present and using the carbon weight to the flue gas flow rate ratio (W/F) of 30 g-min/L. When in equilibrium with a gas mixture containing 250 ppm of NO, the adsorption capacity of NO on the wheat straw and sweet potato activated carbon containing mineral was found to be 1.42 and 1.26 mg NO/g. carbon, respectively. The NO adsorption capacity increases to 5.46 and 3.1 mg NO/g. carbon, respectively for wheat straw and sweet potato activated carbon after the removal of soluble mineral.

After the saturation of the adsorbed NO_x, the activated carbon can be regenerated for reuse. The regeneration can be simply done by heating the carbon bed under anaerobic conditions to above 400°C, when the adsorbed NO_x is reduced to N₂. The loss of carbon mass were determined to be about 0.99% for wheat straw and 0.49% for sweet potato stalk activated carbon per cycle of regeneration at 600°C if the regeneration takes place when flue gas NO after the carbon bed reaches 4.8ppm, the space maximum allowable concentration. The regenerated activated carbon exhibits improved NO adsorption efficiency.

Also, soaked and dried biomass has more than a 5 hour retention time under SMAC with an oxygen concentration of 10% and W/F of 45g.min.L⁻¹ and more than 10 hours retention time under SMAC with a W/F of 60g.min.L⁻¹ for sweet potato. It was also found that with a load of 64.6 kg of wheat carbon at the beginning of the year, 38.5 kg of carbon remains after 52 cycles of regeneration. Thus, the amount of activated carbon attained from wheat straw is plenty for sufficient control of NO_x emissions. So taking all aspects into consideration, we have proven that the use of wheat straw or sweet potato stalk to provide activated carbons for life support systems is an effective method.

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References

1. Fisher, J.W.; Pisharody, S.; Wignarajah, K.; Lighty, J. S.; Burton, B.; Edeen, M.; Davis, K. S. Waste Incineration for Resource Recovery in Bioregenerative Life Support Systems. Technical Paper No. 981758, Proceedings of the 28th International Conference on Environmental Systems, **1998**.
2. Jarvis, J.B.; Carey, T.R.; Frischmuth, R.W.; Yuen, M.K. Feasibility of Applying Selective Catalytic Reduction (SCR) to Oil-Fired, Simple- and Combined-Cycle Combustion Turbines, EPRI-1997, TR-108683-V1, EPRI-DOE-EPA Combined Utility Air Pollutant Control Symposium, 1997
3. Jin, Y.; Yu, Q.Q.; Chang, S.G. Environ. Prog., **1997**, 16, 1-8.
4. Yu, J.J.; Yu, Q.Q.; Jin, Y.; Chang, S.G. Ind. & Eng. Chem. Res. **1997**, 36, 2128-2133.
5. Chang, S.G.; Littlejohn, D.; Lynn, S. Environ. Sci. & Technol. **1983**, 17, 649.
6. Liu, D.K.; Chang, S.G. Environ. Sci. & Technol. **1988**, 22, 1196.
7. Liu, D.K.; Frick, L.P.; Chang, S.G. Environ. Sci. & Technol. **1988**, 22, 219.
8. Chang, S.G.; Littlejohn, D.; Liu, D.K. Ind. & Eng. Chem. Res. **1988**, 27, 2156.
9. Chang, S.G.; Liu, D.K. Nature **1990**, 343, 151-153.
10. Liu, D.K.; Shen, D.X.; Chang, S.G. Environ. Sci. & Technol. 1991, 25, 55.
11. Chang, S.G.; Lee, G.C. Environ. Progr. **1992**, 11, 66-73.
12. Pham, E.; Chang, S.G. Nature **1994**, 369, 139-141.
13. Shi, Y.; Littlejohn, D.; Chang, S.G. Environ. Sci. & Technol. **1996**, 30, 3371-3376.

14. Shi, Y.; Littlejohn, D.; Kettler, P.; Chang, S.G. Environ. Progr. **1996**, 15, 153.
15. Sada, E.; Kumazawa, H.; Kudo, I.; Kondo, T. Ind. Eng. Chem. Process Res. Dev. **1980**, 19, 377-382.
16. Martin, A.E. "Emission Control Technology for Industrial Boilers." **1981**, Noyes Data Corp., Park Ridge, New Jersey, U.S.A.
17. Tsai, S.S.; Bedell, S.A.; Kirby, L.H.; Zabick, D.J. Environ. Progr. **1989**, 8, 126-129.
18. Chen, Z.Y.; Yeh, J.T. Environ. Progr., **1998**, 17, 61-69
19. O'Dowd, W.J.; Markussen, J.M.; Pennline, H.W.; Resnik, K.P. Ind. Eng. Chem. Res., 33:11, 2749-2756, 1994
20. Yeh, J.T.; Drummond, C.J.; Joubert, J.I. Environ. Progr., **1987**, 6, 44.
21. Yeh, J.T.; Demski, R.J.; Joubert, J.I. Environ. Progr., **1985**, 4, 223.
22. Yeh, J.T.; Ma, W.T.; Pennline, H.W.; Haslbeck, J.L.; Joubert, J.I. Gromicko, F.N. Chem. Eng. Comm., **1992**, 114, 65-88.
23. Ma, W.T.; Haslbeck, J.L.; Neal, L.G.; Yeh, J.T. Separations Tech., **1991**, 1, 195.
24. Kaneko, K.; Nakahigashi, Y.; Nagata, K. Carbon, **1988**, 26, 327-332.
25. Lu, G.Q.; Do, D.D. Carbon, **1991**, 29, 207-213.
26. Tsuji, K.; Shiraishi, I. Mitsui-BF Dry Desulfurization and Denitrification Process Using Activated Coke, Vol 3 , pp. 307-324, SO₂ Control Symposium, Sponsored by ERPI, EPA, and DOE, Washington, D. C., December 3-6, **1991**.
27. Illan-Gomez, M.J.; Linares-Salano, A.; Salinas-Martinez de Lecea, C. Energy and Fuels, **1993**, 7,
28. Yougen, K.; Cha, C.Y. Carbon, **1996**, 34, 1034.
29. Neathery, J.K.; Rubel, A.M.; Stencel, J.M. Carbon, **1997**, 35, 1321-1327.
30. Mochida, I; Kawabuchi, Y; Kawano, S; Matsumura, Y; Yoshikawa, M. Fuel, **1997**, 76, 543-548.
31. Berry, W.L.; Goldstein, G.; Dreschel, T.W.; Wheeler, R.V.; Sager, I.C.; Knott, W.V. Soil Science, **1992**, 153, 442-451.
32. Mortley, D.G.; Aglan, H.A.; Bonsi, C.K.; Hill, W.A. Growth of Sweet Potato in Lunar and Mars Simulants, Tech. Memo. 2000-01-2289, International Conference of Environmental Systems, Toulouse, France

33. Wydeven, T.; Golub, M.A. "Generation Rates and Chemical Compositions of Waste Streams in a Typical Crfewed Space Habitat," NASA Technical Memorandum 102799, August 1990.
34. Shields, D.A. Agricultural Outlook, Economics Research Service (ERS), USDA, June-July 2001, p.60
35. Peterson, P.B. Agriculture Progress, **1988**, 63, 8-23.
36. Finger, B.W., Alazrakii, M., "Development and Integration of a Breadboard-Scale Aerobic Bioreactor to Regenerate Nutrients from Inedible Crop Residues," Society of Automotive Engineers, 25th International Conference on Environmental Systems, July, 1995.
37. Pershing, D.W., Wendt, J.O.L., "Pulverized Coal Combustion: The influence of Flame temperature and coal composition on thermal and fuel NO_x", 16th Symposium on Combustion, Combustion Institute, 1976, pp 389-398
38. Fisher, J.W.; Pisharody, S.; Moran, M.J.; Chang, S.G.; Shi, Y. "Reaction Carbon from Life Support Wastes for Incinerator Flue Gas Cleanup", 30th International Conference on Environmental System (ICES), July 10-13,2000, Toulouse, France

Figure Captions

Figure 1. Schematic diagram of apparatus used for the production of activated carbons from biomass and for the evaluation of its NO adsorption capability

Figure 2. Burnoff of wheat straw and sweet potato stalk as a function of temperature under anaerobic conditions

Figure 3. BET surface areas of wheat straw activated carbon produced at a variety of temperatures

Figure 4. BJH cumulative pore area of wheat straw activated carbon produced at different pyrolysis and activation times

Figure 5. NO removal efficiency by wheat straw activated carbon produced with different pyrolysis and activation temperatures; Flue gas composition: 250ppm NO, 5% O₂, 10% CO₂, N₂ the balance; W/F=8g.min.L⁻¹

Figure 6. NO removal efficiency by wheat straw activated carbon produced with different pyrolysis and activation times; Flue gas composition: 250ppm NO, 5% O₂: 5%, 10% CO₂, N₂ the balance; W/F=8g.min.L⁻¹

Figure 7. NO removal efficiency by sweet potato activated carbon, SP-2-600-1-650, before and after soaking and drying (SD); Flue gas composition: 250ppm NO, 10% CO₂, 10% O₂, N₂ the balance; at 25°C

Figure 8. NO removal efficiency by wheat straw activated carbon, WS-2-600-1-650, before and after soaking and drying (SD); Flue gas composition: 250ppm NO, 10% CO₂, 10% O₂: 10%, with N₂ the balance; at 25°C

Figure 9. The effect of oxygen on NO removal efficiency by SP-2-600-1-650(SD); Flue gas composition: 250ppm NO, 10% CO₂ with N₂ the balance; W/F=30g.min.L⁻¹

Figure 10. The effect of oxygen on NO removal efficiency by WS-2-600-1-650(SD); Flue gas composition: 250ppm NO, 10% CO₂ with N₂ the balance; W/F=30g.min.L⁻¹

Figure 11. The effect of water vapor on NO removal efficiency by SP-2-600-1-650(SD); Flue gas composition: 250ppm NO, 10% CO₂, 5%O₂ with N₂ the Balance; W/F=30g.min.L⁻¹, at 25°C

Figure 12. The effect of water vapor on NO removal efficiency by WS-2-600-1-650(SD); Flue gas composition: 250ppm NO, 10%CO₂, 5%O₂ with N₂ the balance; F/W=30g.min.L⁻¹; at 25°C

Figure 13. Fraction of NO desorbed when integrated over temperatures as the temperature of the wheat straw and sweet potato stalk carbon bed was raised at 40°C/min. N₂ was used as carrier gas at 1L./min. Before desorption, NO adsorption by the activated carbon had been performed.

Figure 14. The effect of the ratio of carbon weight to flue gas flow rate (W/F) on the reduction efficiency of NO by sweet potato activated carbon at various temperatures, 250ppm NO with N₂ the balance.

Figure 15. The effect of the ratio of carbon weight to flue gas flow rate (W/F) on the reduction efficiency of NO by wheat straw activated carbon at various temperatures; 250ppm NO with N₂ the balance.

Figure 16. The effect of NO concentration on the NO reduction efficiency by sweet potato and wheat straw activated carbons; N₂ is the carrier gas; at 450°C.

Figure 17. The effect of W/F and oxygen on SMAC time using SP-2-600-1-650; 250ppm NO, 10% CO₂ with N₂ the balance; at 25°C

Figure 18. The effect of W/F and oxygen on SMAC time using sweet potato activated carbon after removal of minerals by soaking in water and drying, SP-2-600-1-650(SD); 250ppm NO:250ppm, 10% CO₂ with N₂ the balance; at 25°C

Figure 1

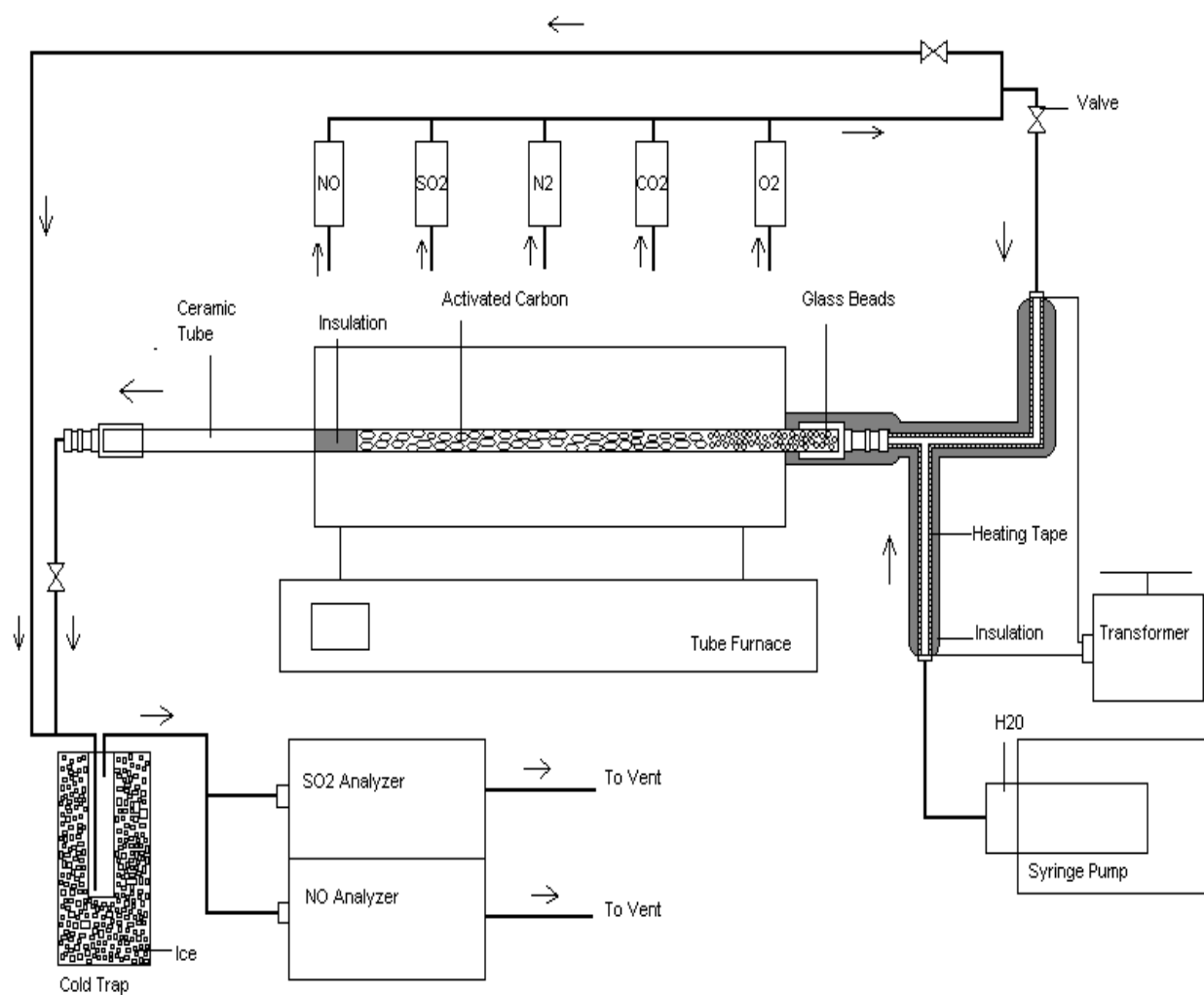


Figure 2

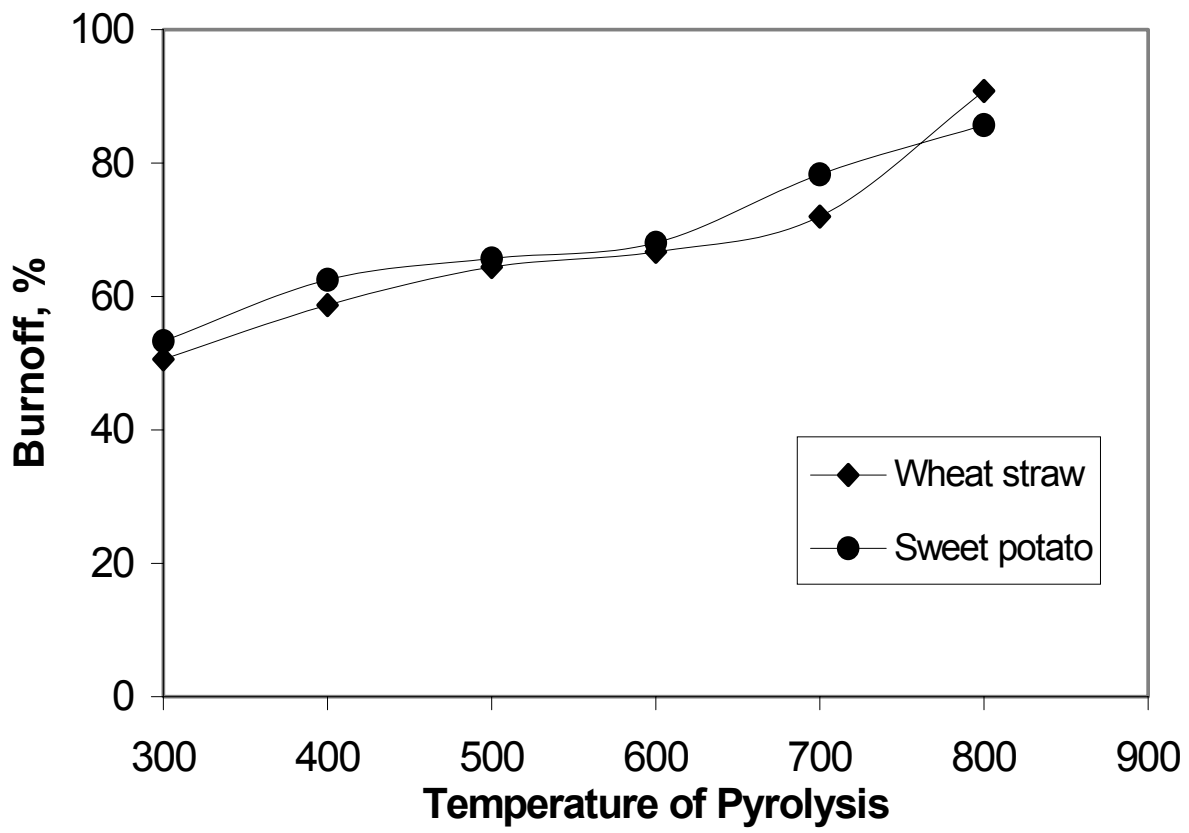


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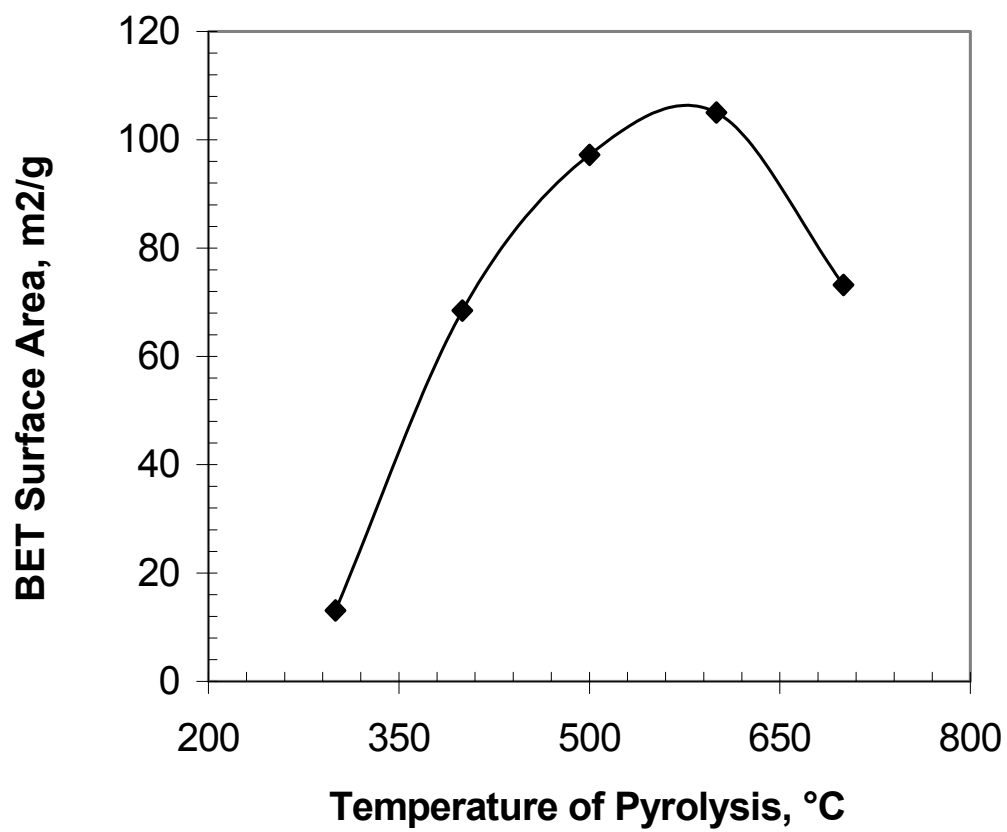


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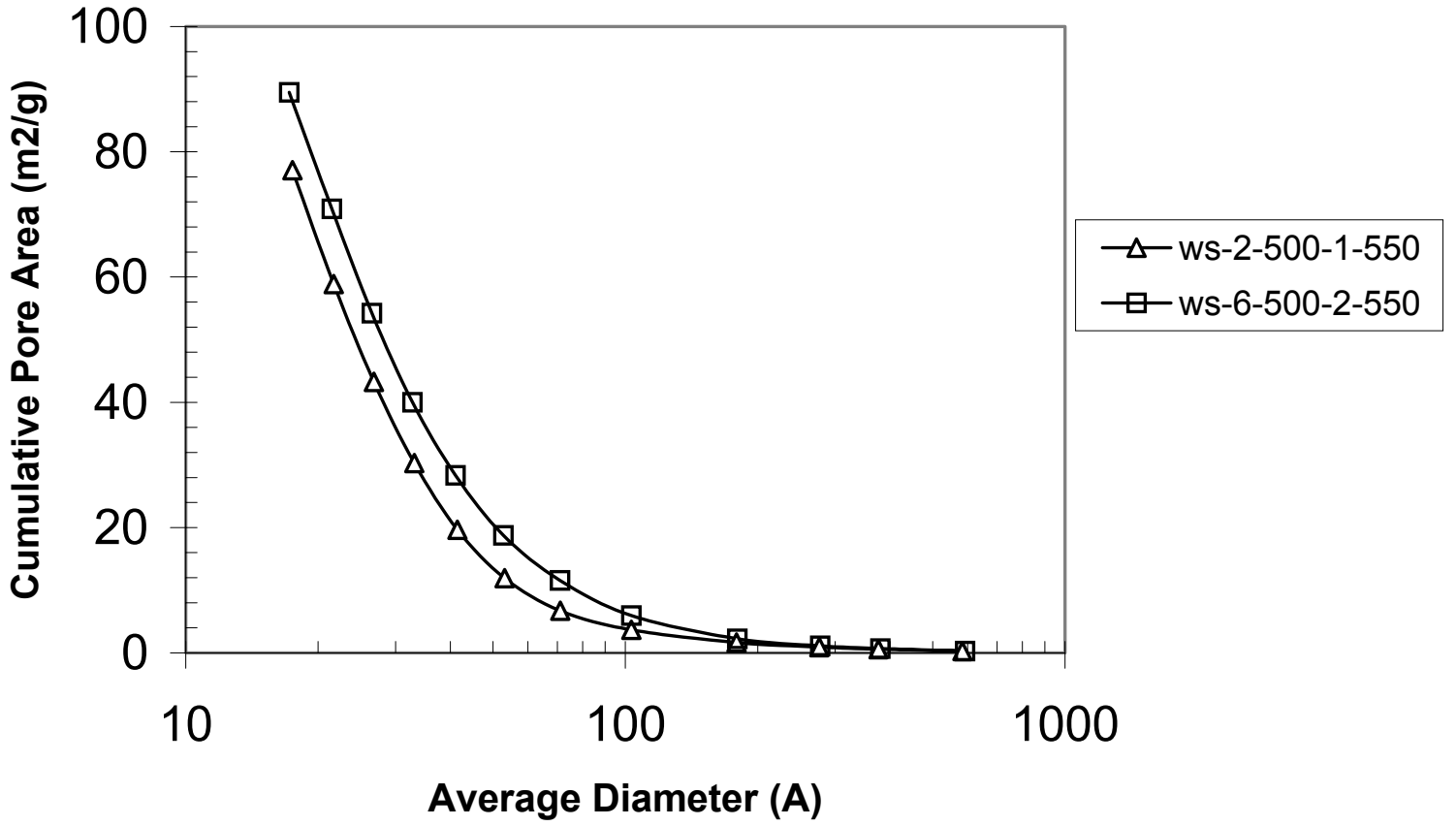


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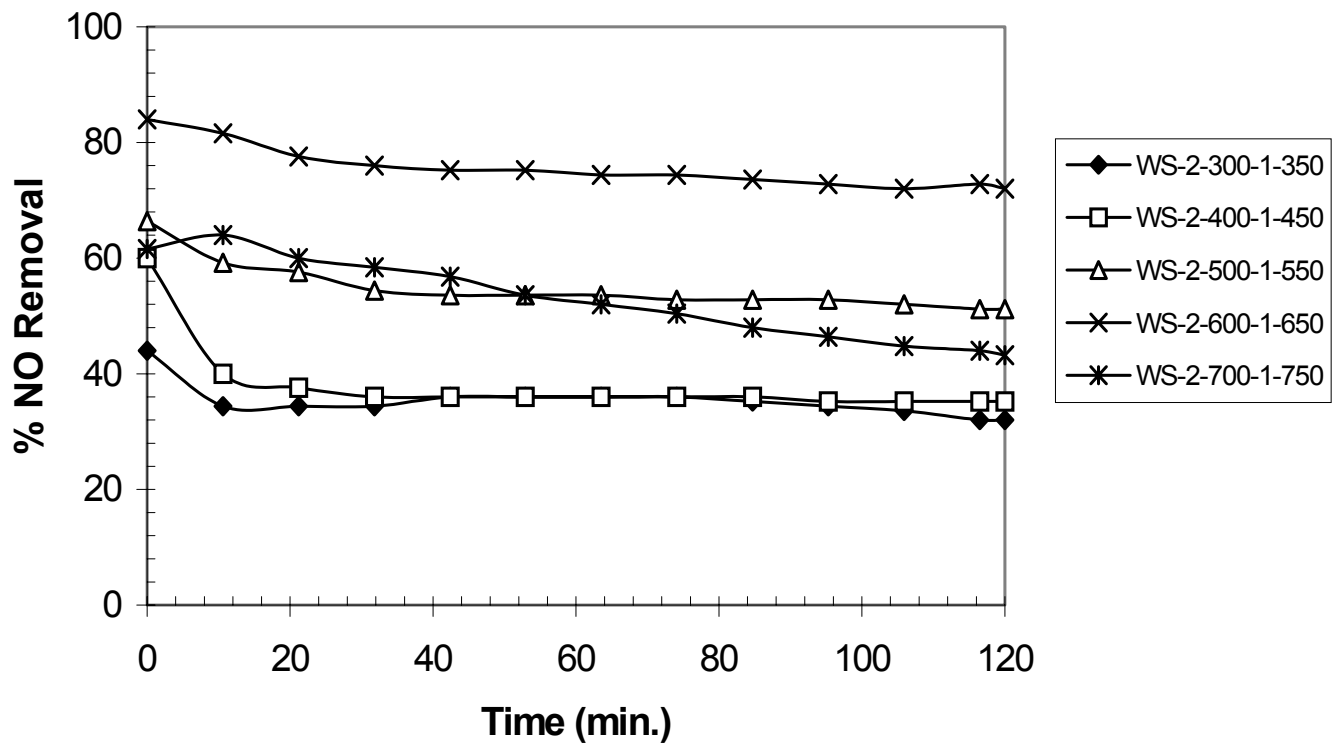


Figure 6

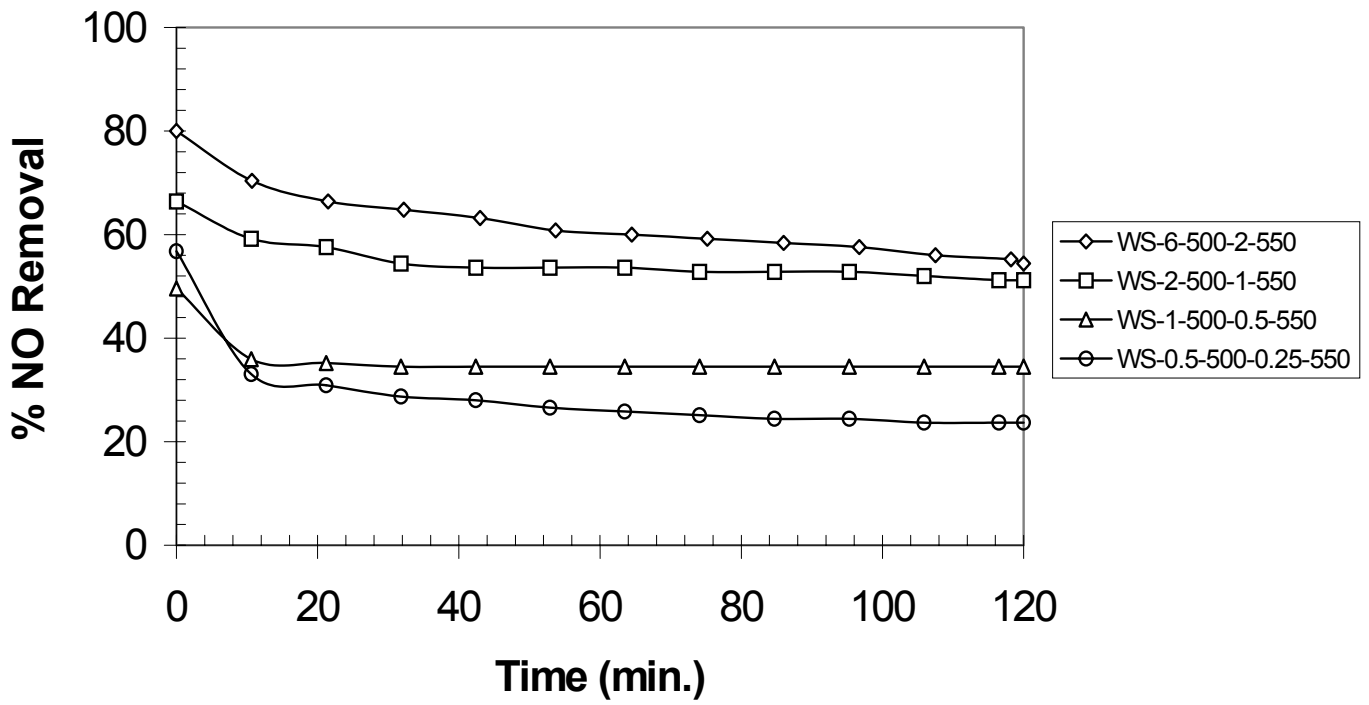


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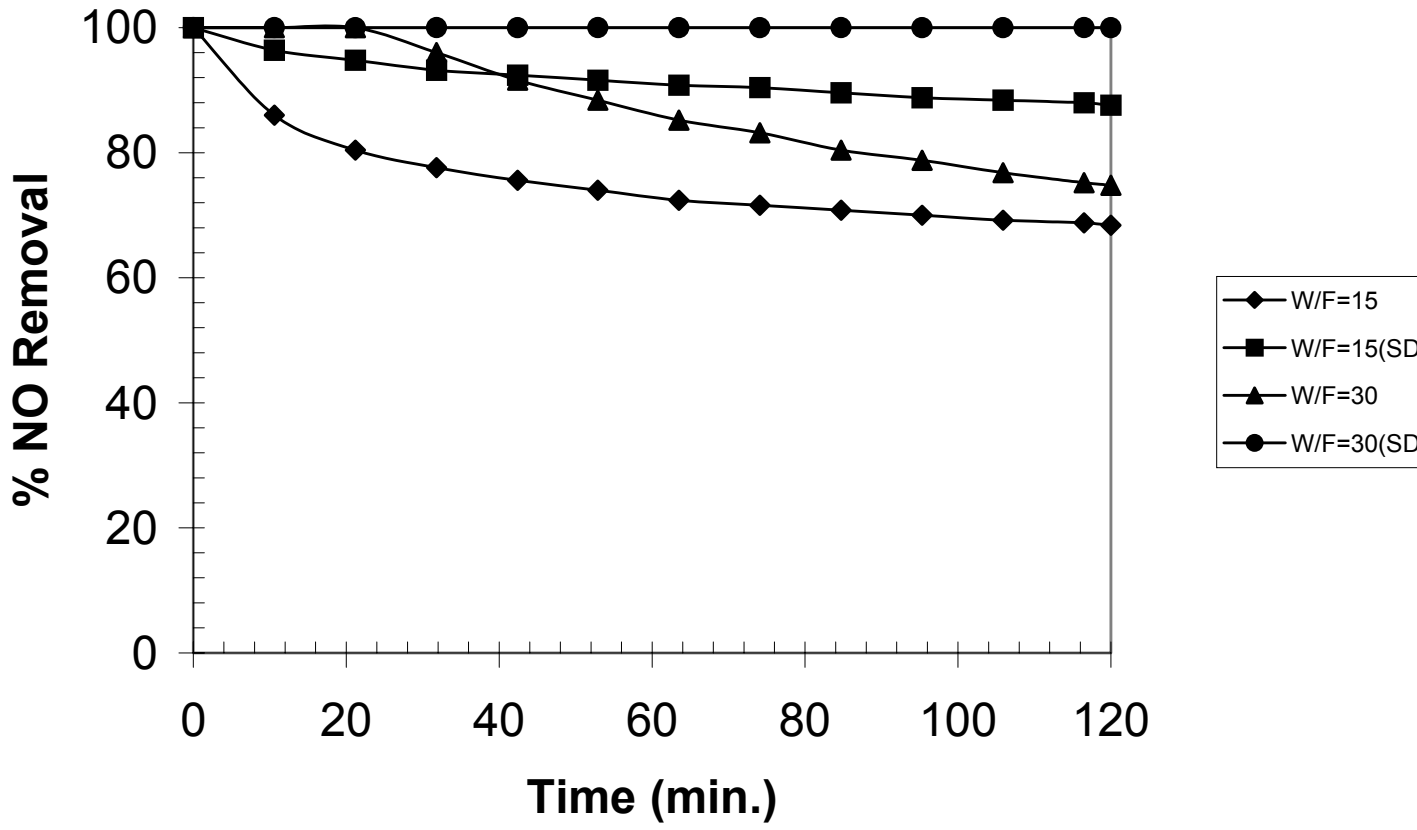


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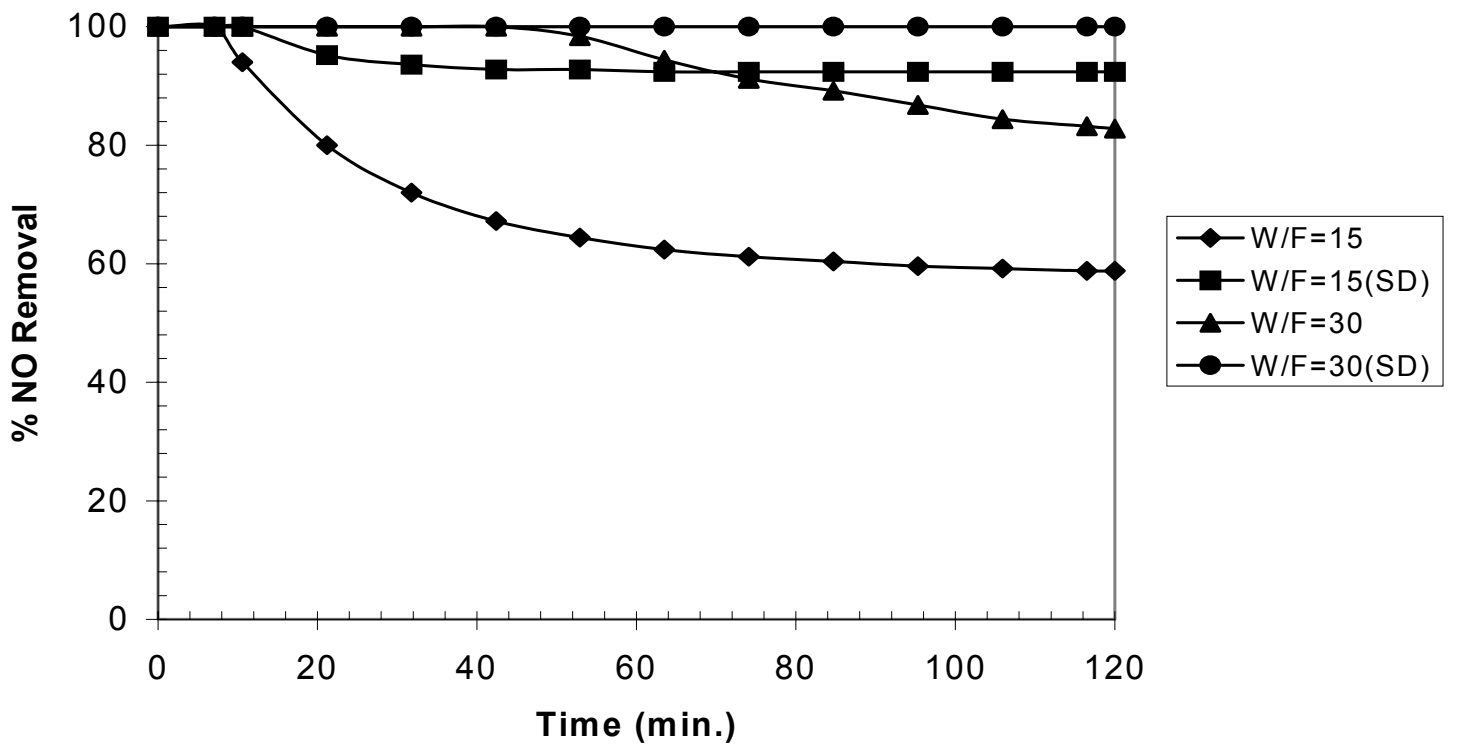


Figure 9

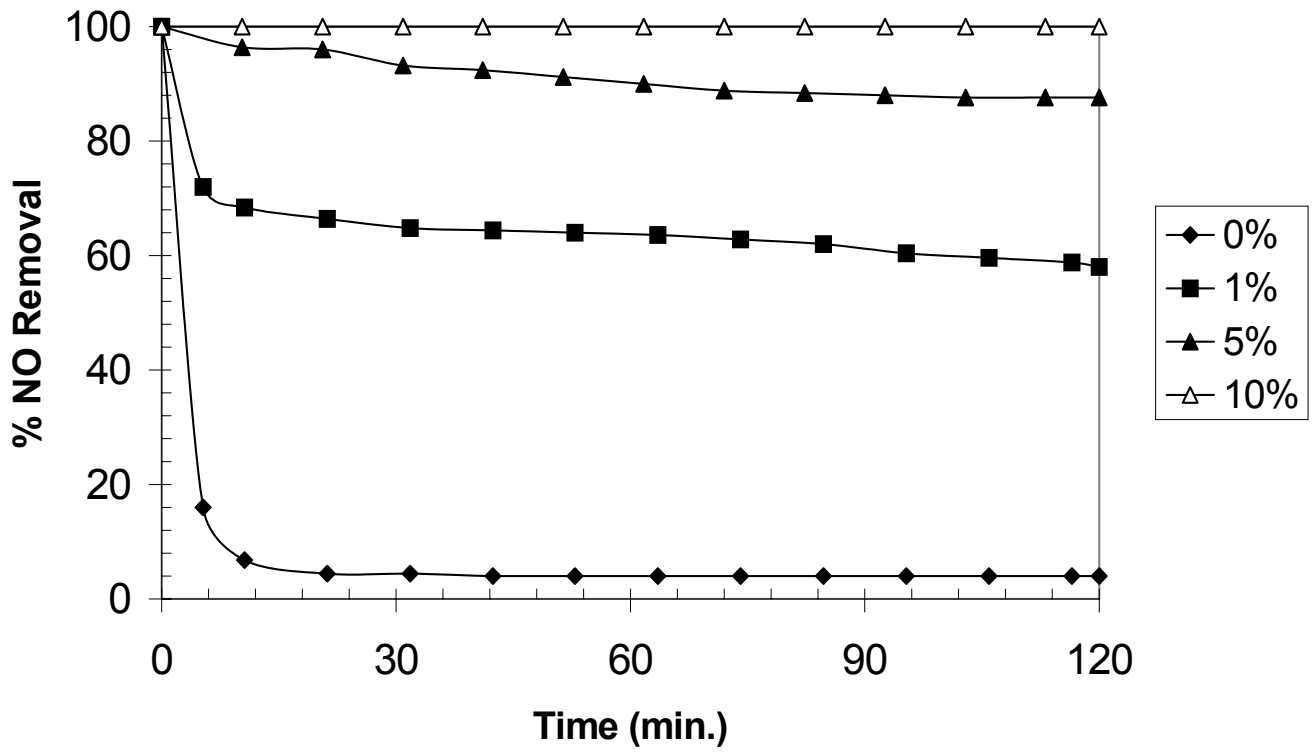


Figure 10

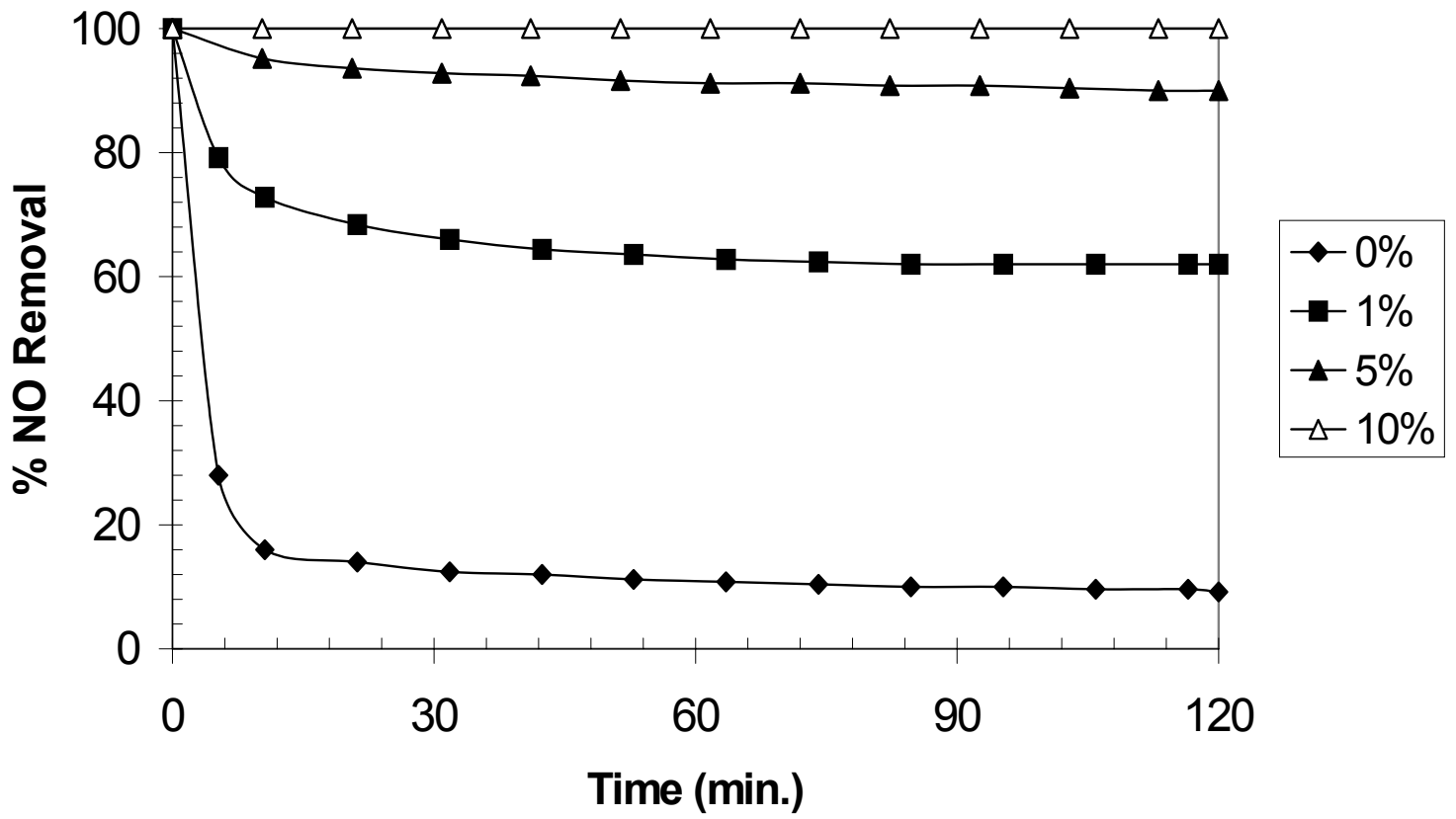


Figure 11

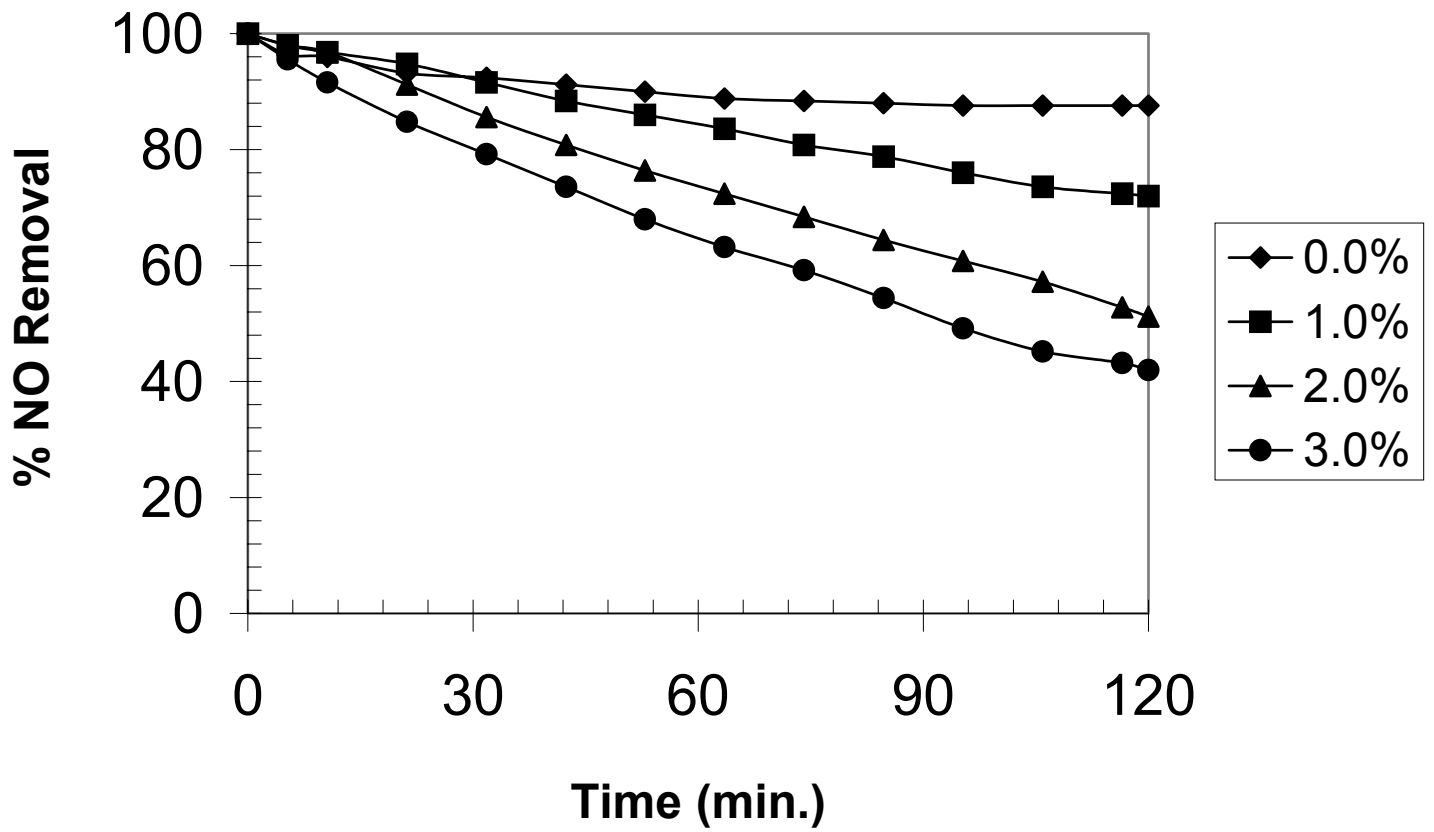


Figure12

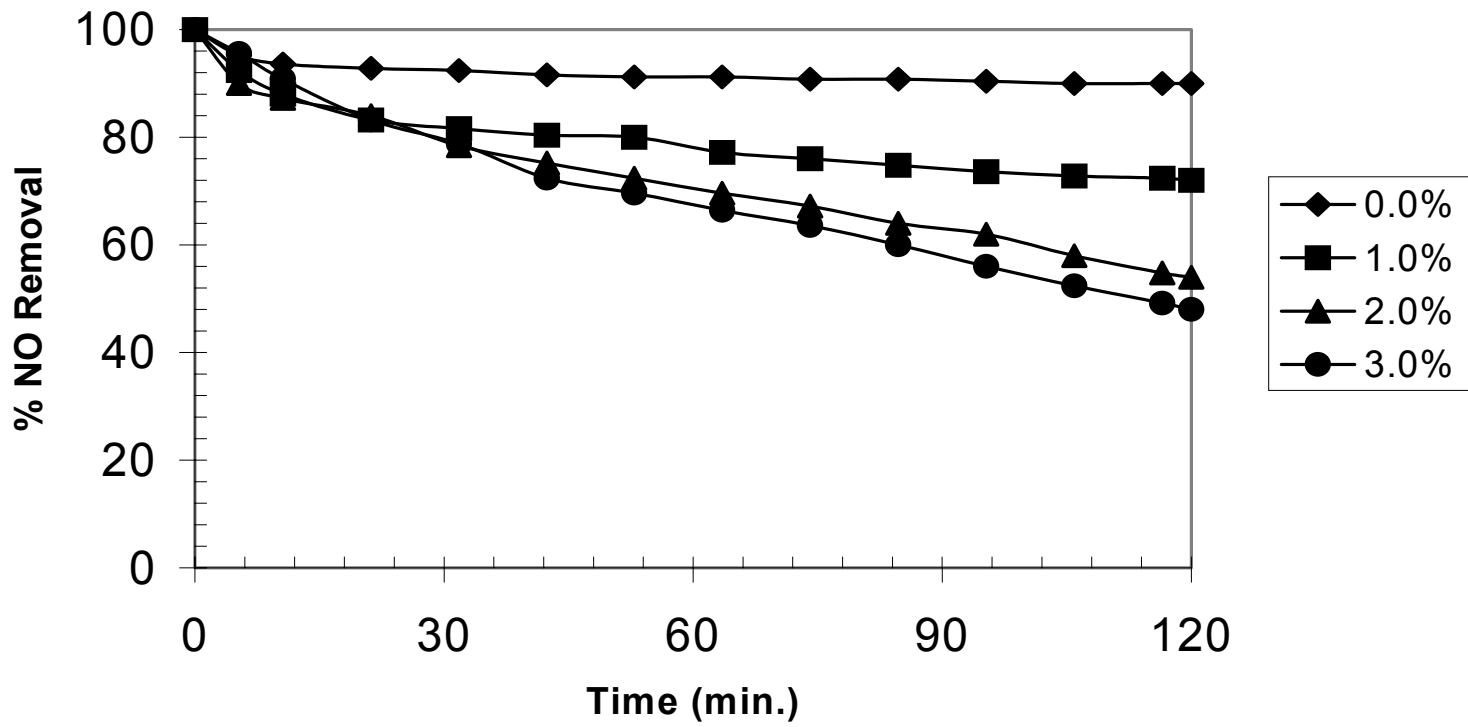


Figure 13

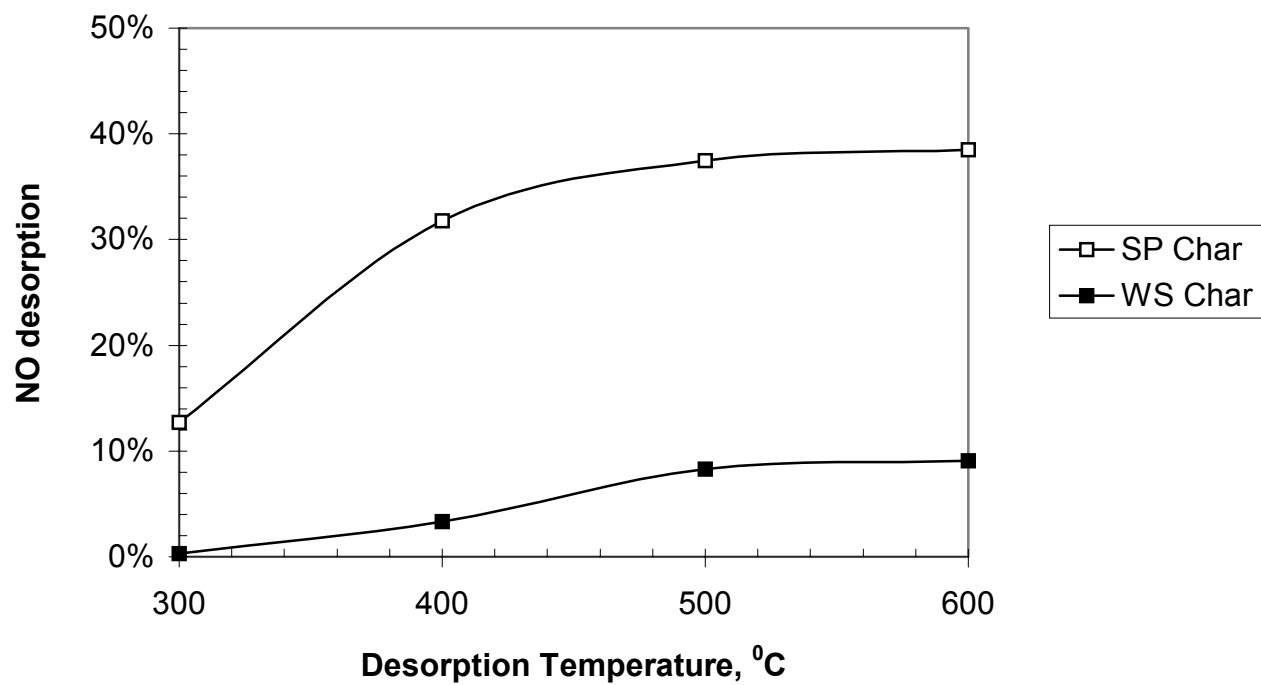


Figure 14

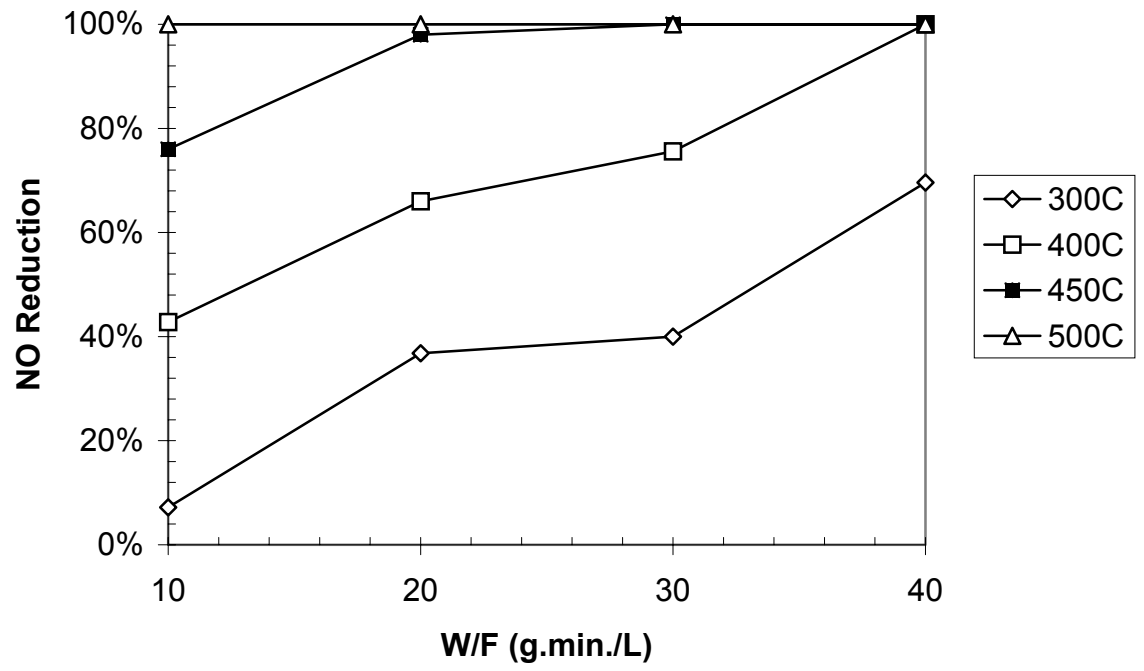


Figure 15

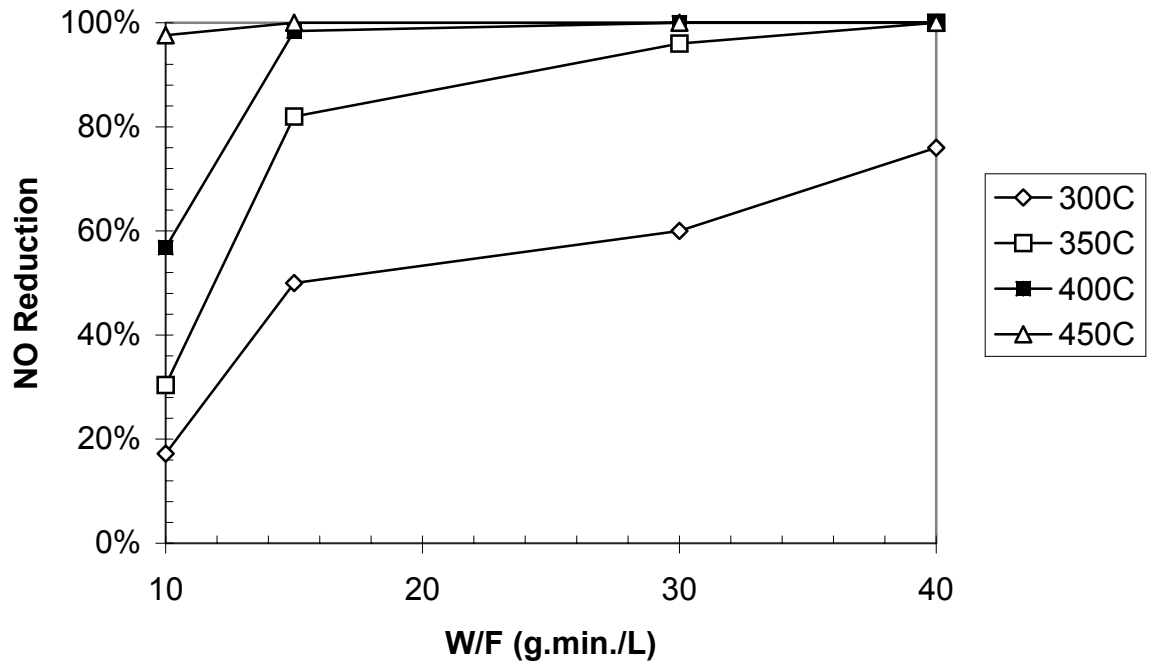


Figure 16

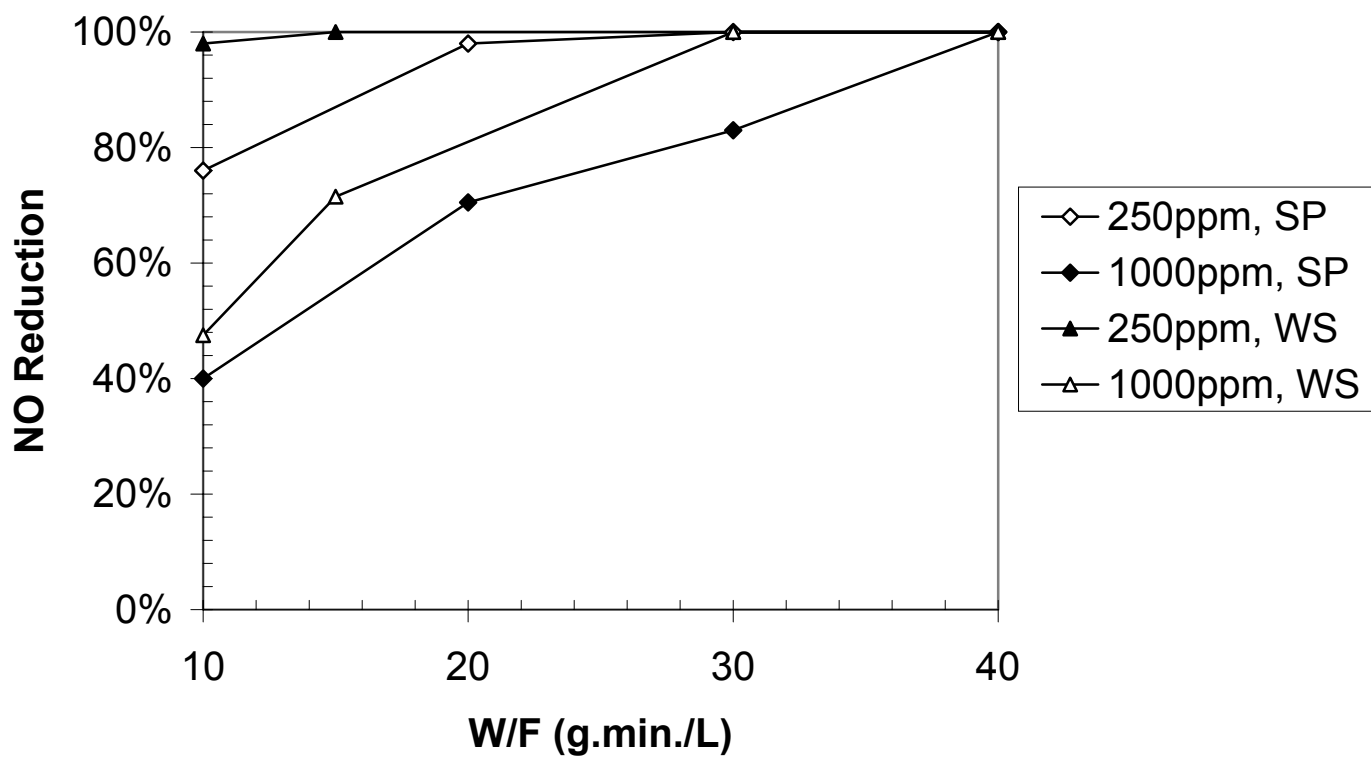


Figure 17

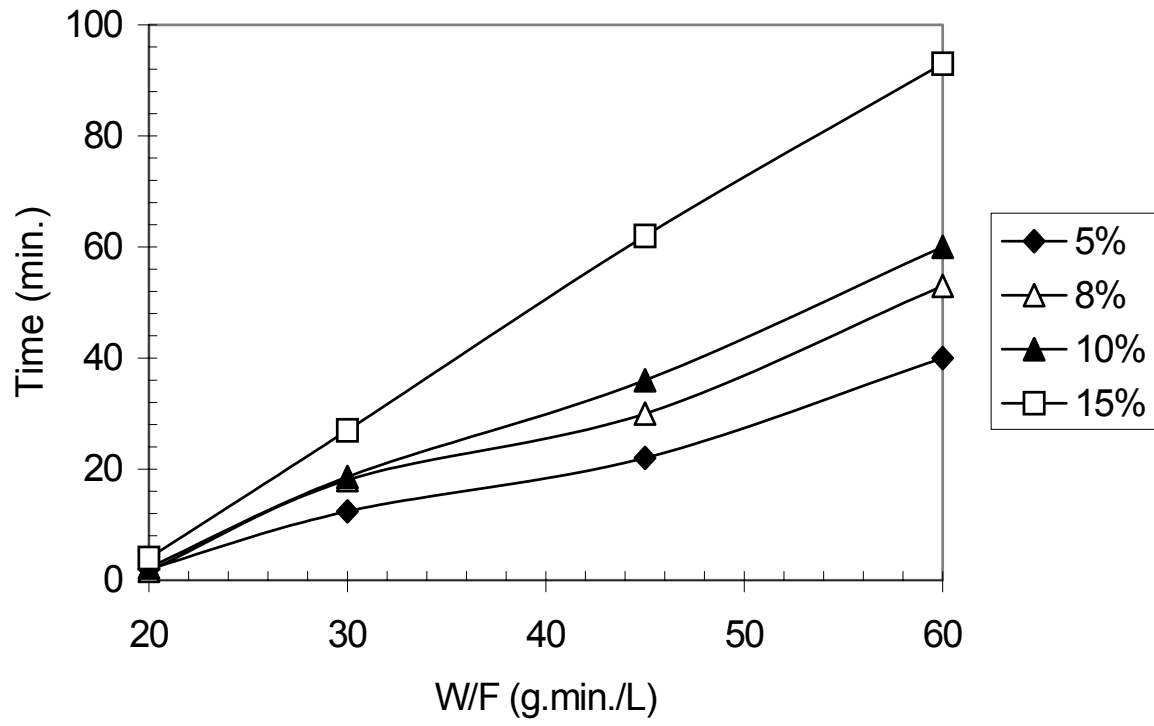


Figure 18

