

## AUTOREFERAT

### 1. Name and surname

Krzysztof Jastrząb

### 2. Diplomas and academic degrees

1986 – MSc Eng., Faculty of Chemistry, Silesian University of Technology, Gliwice

Specialization: inorganic chemical technology, industrial electrochemistry

MSc thesis " *The influence of organic substances and electricity density on the structure of cathode in the copper electrorefining process*", supervisor: prof.dr hab.inż. W Gnot

1995 – PhD in technical sciences, Scientific discipline: chemical technology

Faculty of Chemistry, Silesian University of Technology, Gliwice

PhD thesis " *Investigation of sorption of sulphur dioxide on a fixed bed of carbonaceous sorbent SWS-6*", dissertation with honours, supervisor: prof.dr hab.inż. J.Szarawara

### 3. Information on employment in scientific units

Faculty of Chemistry of the Silesian University of Technology in Gliwice:

1986-1988	chemist engineer
1988-1996	assistant
1996-2011	assistant professor
2011-2012	assistant

Institute for Chemical Processing of Coal in Zabrze

2012-2013	senior engineering and technical specialist
2013-	assistant professor
2015-	Head of the Gas Cleaning Team

### 4. Indication of the achievement resulting from art. 16 sec. 2 of the Act of 14 March 2003 on academic degrees and academic title, and on degrees and title in the field of art (Journal of Laws of 2016, item 882, as amended in Journal of Laws of 2016, item 1311. ):

a) title of the scientific achievement

**Physicochemical basis of adsorptiv-catalytic technology of industrial flue gases purification using Polish activated cokes**

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b) publications that are part of the scientific achievement:

1. J.Szarawara, S.Anioł, K.Jastrząb, Z.Dębowski, *Badania sorpcji SO<sub>2</sub> na sorbentach węglowych przeznaczonych do odsiarczania spalin*, Przem. Chem., 1990, 69, 509-512
2. K.Jastrząb, J.Szarawara, *Investigations of the SO<sub>2</sub> sorption on a carbon sorbent, Part I - Properties of the process*, Polish J.Appl.Chem., 1996, 40, 187-204
3. K.Jastrząb, M.Zin, *Porównanie właściwości koksów aktywnych stosowanych w przemysłowych instalacjach oczyszczania gazów spalinowych*, Inżynieria i Ochrona Środowiska, 2000, 3, 377-388
4. K.Jastrząb, *Metody oceny właściwości sorbentów węglowych pod względem przydatności do przemysłowego odsiarczania spalin*, Inżynieria Chemiczna i Ekologiczna, 2001, 8, 1043-1046
5. K.Jastrząb, *Properties of activated cokes used for flue gas treatment in industrial waste incineration plants*, Fuel Processing Technology, 2012, 101, 16-22
6. S.Stelmach, K.Jastrząb, *Porównanie właściwości komercyjnych koksów aktywnych*, Inżynieria i Ochrona Środowiska, 2013, 16, 373-383
7. K.Jastrząb, J.Szarawara, *Investigations of the SO<sub>2</sub> sorption on a carbon sorbent, Part IV - Equilibrium of the process*, Polish Journal of Applied Chemistry, 1996, 40, 227-235
8. K.Jastrząb, J.Szarawara, *Investigations of the SO<sub>2</sub> sorption on a carbon sorbent, Part II - Dynamics of the process*, Polish Journal of Applied Chemistry, 1996, 40, 205-213
9. K.Jastrząb, J.Szarawara, *Investigations of the SO<sub>2</sub> sorption on a carbon sorbent, Part III - Empirical model of the process*, Polish Journal of Applied Chemistry, 1996, 40, 215-225
10. K.Jastrząb, J.Szarawara, *Investigations of the SO<sub>2</sub> sorption on a carbon sorbent, Part VI - Determination of the region of the process*, Polish Journal of Applied Chemistry, 1997, 41, 159-168
11. K.Jastrząb, J.Szarawara, *Model kinetyczny procesu sorpcji SO<sub>2</sub> na sorbencie węglowym*, chapter in the reviewed proceedings of the II Congress of Chemical Technology, Dolnośląskie Wydawnictwo Edukacyjne, Wrocław 1998, t.2, pp.762-766, 1998. ISBN 83-7125-035-5
12. K.Jastrząb, *Investigations of the SO<sub>2</sub> sorption on a carbon sorbent, Part IX – The thermal effect of the process*, Polish Journal of Applied Chemistry, 2000, 44, 19-30
13. K.Jastrząb, J.Szarawara, *Investigations of the SO<sub>2</sub> sorption on a carbon sorbent, Part VII - Scaling-up of the process*, Polish Journal of Applied Chemistry, 1997, 41, 327-336
14. K.Jastrząb, J.Szarawara, S.Anioł, *Badania procesu redukcji tlenków azotu gazowym amoniakiem na sorbentach węglowych*, Przem.Chem., 1994, 73, 66-68
15. K.Jastrząb, J.Szarawara, *Determination of a steady-state operation of a reactor for NO reduction by NH<sub>3</sub> on a carbon sorbent*, Polish J. Chem.Technol., 2002, 1, 4-7
16. K.Jastrząb, J.Szarawara, *Properties of the process of reduction of nitrogen oxides on a carbon sorbent*, Archive of Environmental Protection, 1998, 24, 59-75

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17. K.Jastrząb, J.Szarawara, *Determination of the rate regime of the catalytic process of reducing of nitrogen oxide by means of ammonia on the active coke*, Polish J. Chem. Technol., 2002, 3, 8-12
18. K.Jastrząb, *Kinetics of the reduction of nitrogen oxides with ammonia on a carbon sorbent*, Polish Journal of Applied Chemistry, 1998, 42, 3-12
19. K.Jastrząb, J.Szarawara, *Kinetics of nitrogen oxide reduction by means of ammonia on a Polish carbon sorbent*, Polish Journal of Environmental Studies, 2002, 11, 689-693
20. K.Jastrząb, J.Szarawara, *Badania nad powiększaniem skali reaktora do prowadzenia redukcji tlenków azotu na sorbencie węglowym AKP*, Inżynieria i Aparatura Chemiczna, 2001, 3, 5-9
21. K.Jastrząb, *Redukcja tlenku azotu metanem na koksie aktywnym AKP*, Przem.Chem., 2003, 82, 1023-1025
22. K.Jastrząb, J.Szarawara, *Katalityczna redukcja tlenków azotu węglowodorami na koksie aktywnym*, chapter in the reviewed monograph „*Węgiel aktywny w ochronie środowiska*”, Pol. Częstochowska Ed., 2004, s.375-384. ISBN-83-7193-247-2.
23. K.Jastrząb, J.Szarawara, *Model kinetyczny procesu redukcji tlenku azotu na katalizatorze węglowym modyfikowanym niklem*, Przem. Chem., 2006, 85, 726-728
24. K.Jastrząb, J.Szarawara, *Badania kinetyki redukcji tlenków azotu węglowodorami na koksie aktywnym modyfikowanym kobaltem*, chapter in the reviewed monograph „*Węgiel aktywny w ochronie środowiska i przemyśle*”, Pol. Częstochowska Ed., 2006, pp.338-344. ISBN 978-83-7193-303-5.
25. K.Jastrząb, P.Skiba, *Opis kinetyki redukcji NO węglowodorami na katalizatorze węglowo-żelazowym za pomocą sztucznych sieci neuronowych*, Przem.Chem., 2006, 85, 723-725
26. K.Jastrząb, *Usuwanie par rtęci na złożu koksu aktywnego AKP-5*, chapter in the reviewed monograph „*Węgiel aktywny w ochronie środowiska i przemyśle*”, Pol. Częstochowska Ed., 2008, pp.225-234. ISBN 978-83-7193-377-6.
27. K.Jastrząb, *Badania nad usuwaniem par rtęci metalicznej z gazów odlotowych na złożu koksu aktywnego AKP-5S*, Przem.Chem., 2011, 90, 1527-1530
28. K.Jastrząb, S.Stelmach, J.Figa, *Adsorbenty węglowe otrzymane ze zużytych opon przeznaczone do usuwania rtęci z gazów spalinowych*, chapter in the reviewed monograph „*Węgiel aktywny w ochronie środowiska i przemyśle*”, Pol. Częstochowska Ed., 2008, pp.157-167. ISBN 978-83-7193-377-6.
29. S.Stelmach, J.Figa, K.Jastrząb, A.Sobolewski, *Sposób otrzymywania sorbentu*, Polish patent no. 213528 z dnia 2013.11.06
30. J.Szarawara, S.Anioł, K.Jastrząb, *Badania desorpcji dwutlenku siarki z sorbentów węglowych w procesie odsiarczania spalin*, Przem.Chem., 1992, 71, 321-323
31. K.Jastrząb, *Regeneration of spent active coke used for the removal of mercury from flue gases*, Proceedings of the 40<sup>th</sup> International Conference of SSChE, Tatranské Matliare, Slovakia, May 2013, pp.276-282. ISBN 978-80-89475-09-4

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32. K.Jastrząb, *Badania regeneracji termicznej adsorbentów węglowych przeznaczonych do usuwania rtęci z przemysłowych gazów spalinowych*, chapter in the reviewed monograph „*Rtęć w środowisku*”, UG Ed., Gdańsk 2013, pp.229-234. ISBN 978-83-7865-090-4
33. K.Jastrząb, I.Mazurek, *Badania desorpcji termicznej związków rtęci ze zużytych koksów aktywnych stosowanych do końcowego oczyszczania spalin w spalarniach odpadów*, *Inżynieria i Ochrona Środowiska*, 2013, 16, 271-283
34. K.Jastrząb, I.Mazurek, *Badania regeneracji termicznej koksu aktywnego stosowanego do usuwania rtęci z gazów spalinowych*, chapter in the reviewed monograph "*Ochrona powietrza w teorii i praktyce*", IPIŚ PAN Ed., Zabrze 2014, pp.57-68. ISBN 978-83-60877-13-5
35. J.Szarawara, S.Anioł, K.Jastrząb, J.Marszałek, *Mokra regeneracja sorbentu węglowego przeznaczonego do odsiarczania gazów spalinowych*, *Przem.Chem.*, 1996, 75, 178-180
36. K.Jastrząb, *Changes of activated coke properties in cyclic adsorption flue gas treatment*, *Fuel Processing Technology*, 2012, 104, 371-377
37. K.Jastrząb, *Oznaczanie temperatury zapłonu koksów aktywnych stosowanych do oczyszczania gazów spalinowych*, *Przem.Chem.*, 2012, 91, 69-74

c) discussion of the scientific purpose of the above works, results achieved, discussion of their possible use

BAT conclusions for large combustion plants (LCP) adopted in August 2017, became more demanding not only in field of emission standards for: particulate matter, sulfur dioxide and nitrogen oxides, but also in other contaminants like: mercury, hydrogen chloride, hydrogen fluoride and ammonia. Unfortunately because of different properties of above -mentioned contaminants, they have to remove using different processes and gas cleaning systems. New legislation not only concerns power production installations, but also gasification installations and municipal waste incineration plants.

One of the dry method which enables removal all of flue gases contaminants in one process is based on carbonaceous adsorbents. BF Technology (Bergbau Forshung), introduced in the '80s of the 20th century, in Germany, is the most known. More developed version of BF Technology is: MET-Mitsui-BF introduced in USA and ReACT technology in Japan. Intense works on that subject are conducted in South Korea and China.

Each of above-mentioned technology is based on carbonaceous sorbent bed, also called activated coke (AC), through which gas phase passes. Activated coke (AC) is coal-based sorbent with optimal adsorptive and catalytic parameters, graining, high ignition point as well as high mechanical strength. Flue gas cleaning process has several stages. The first stage is adsorption of SO<sub>2</sub> on the surface of activated coke. After catalytic oxidation process, SO<sub>2</sub> is accumulated in the porous structure of activated coke (AC) as a sulfur acid. During the second stage of cleaning, ammonia is injected into the desulfurized flue gas passing through activated coke bed. Catalytic reaction of NO<sub>x</sub> reduction is taking place on the surface of the activated carbon, which is do analogous with to classic SCR process. In the same time other contaminants like: heavy metals (Hg), persistent organic pollutants (POPs), hydrogen chloride etc., are removed from the flue gases. Activated coke, which became used and saturated with sulfur compounds, is regenerated and recirculated to the process. Chemical desorption is the

most common in that cakes.  $\text{SO}_2$ , that form within the process of activated carbon regeneration, is converted in different process.

There are many benefits of gas cleaning method based on adsorption. First of all it is dry method which eliminates installation corrosion and slagging of deposits. Gas cleaning process is conducted within the temperature range 120-180°C (over saturation point), which eliminates warming up and cooling of flue gases before passing them to the stack and it is zero waste process. Main disadvantage of gas cleaning method based on adsorption is high operational costs, which come from active coke deactivation and high energy demand of regeneration process.

At the end of past century, I started complex research on domestic technology of flue gas cleaning systems based on activated coke, at department of Chemistry of Silesian University of Technology. Above-mentioned research can be divided in 6 stages:

- study on characteristic parameters of activated cokes and selection of polish activated coke appropriate to technology of gas cleaning systems based on adsorption;
- study on adsorptive and catalytic process of sulfur dioxide removal using activated cokes;
- study on catalytic reduction of nitrogen oxides, using ammonia;
- innovative research on catalytic nitrogen oxides reduction on activated cokes, using hydrocarbons (HC-SCR technology);
- research on mercury removal from flue gases combined with coal-based sorbents for mercury removal from industrial flue gases, received from waste tires;
- study on used activated cokes regeneration processes.

Primary scientific goal of the above-mentioned research was thorough study on characteristic parameters of individual unit process of adsorptive flue gas cleaning and express their using mathematics, kinetics and equilibrium correlations. This knowledge can be used not only for process design but also for determination of optimal process conduction parameters in large scale. I would like to underline the fact that among all mentioned research I took an interest in several matters being novelty in science, for instance:

- low-temperature, catalytic nitrogen oxides reduction on activated cokes and catalysts received from activated cokes, using hydrocarbons (HC-SCR technology);
- preparation of granulated and grained coal adsorbents based on char from waste tires and their application to mercury and its compound removal from flue gases;
- determination of characteristic parameters of activated coke change in cyclic process of  $\text{SO}_2$  sorption- thermal regeneration;

All test results enabled to develop design basis for technology of catalytic and adsorptive industry flue gas cleaning using Polish activated cokes. Results of particular studies and tests were dominating theme in cycle of publications being the basis of scientific achievement. Specific guide describing all research works along with bibliography is attached to the reference list of papers. Synthetic abstract of conducted research being the basis of scientific achievement, were stated below along with short description.

a) Elaboration of testing characteristic catalytic and adsorptive parameters of activated cokes, as well as selection of activated cokes for industrial flue gas cleaning.

Main technological problem, during elaboration of gas cleaning system based on adsorption, was selection of activated cokes having appropriate catalytic and adsorptive

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characteristics. The aim of preliminary research was to select sorbent with appropriate characteristics [1]. Among variety of Polish commercial and laboratory manufactured carbonaceous adsorbents, laboratory char K-13 was selected because of good results in SO<sub>2</sub> adsorption. It became a ground sill to create new, semi industrial carbonaceous sorbent SWS-6 [2] and after that commercial activated coke AKP-5 produced in Gryfskand, Hajnówka [3]. Crucial problem to solve along testing activated cokes was the selection appropriate testing procedure, which allow to compare adsorptive and catalytic parameters of different materials. I was responsible for opening the laboratory for activated cokes testing for flue gas cleaning abilities in semi industrial scale, unique in Poland and one of the few in the world. Using above-mention infrastructure and elaborated procedures I tested activated coke parameters of different producers, not only domestic ones (Gryfskand) [3,5] but also foreign (Carbotech, Mitsui, Chinese producers) [6]. Activated cokes were tested on: SO<sub>2</sub> adsorptive and catalytic parameters, activity within catalytic NO<sub>x</sub> reduction process with ammonia and adsorptive abilities of mercury and it's compounds.

b) Studying adsorptive and catalytic desulfurization of flue gases on activated cokes.

Sulfur dioxide removal using carbonaceous sorbent SWS-6 was the main subject of my PhD dissertation. Within the next years after PhD I continued that studies, presenting the results of my work in scientific journals. Papers were describing following matters:

- I ran supplemented tests on determination of various parameters influencing SO<sub>2</sub> sorption on activated cokes. Using that knowledge I developed multi-parameters equation, enabling calculation of SO<sub>2</sub> concentration not only in cleaned flue gases but also in activated coke bed, as a function of time and initial gas phase composition [2]. I proved that in case of gas phase composition above 5% O<sub>2</sub> and 8% H<sub>2</sub>O, large fluctuation of oxygen and steam concentration do not effect process course, which brings to conclusion that SO<sub>2</sub> adsorption from flue gases with standard composition, can be describe by simplified equation considering only time, temperature and SO<sub>2</sub> concentration.
- I started new interpretation of research concerning dynamics of SO<sub>2</sub> sorption enriched with additional test of sorption but in the adsorber with variable height of activated coke bed and elaborated new, multi-parameters equations describing dynamics of SO<sub>2</sub> sorption process. Equations enables determination of average and real level of activated coke saturation by sulfur compounds everywhere in the adsorber as a function of time [7,8]. That specific approach was never practiced in science.
- On the basis of test results described in previous point as well as theoretical deliberations, I developed a multi-parametric model that enables calculation of SO<sub>2</sub> reduction as function of: time, initial C concentration and height of the adsorbent's bed [9]. SO<sub>2</sub> medium concentration in activated coke bed can be calculated through numerical integration of selected function.
- Considering SO<sub>2</sub> sorption as catalytic heterogeneous process, I defined the slowest stage of the process [10]. I also proved that process runs through kinetic area with negligible influence of diffusion phenomena. On the basis of temperature criterion, I estimated apparent activation energy of SO<sub>2</sub> sorption. Using Langmuir-Hinshelwood model and theory of catalyst deactivation, I developed theoretical SO<sub>2</sub> sorption catalytic model [11].

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- I developed methodology of SO<sub>2</sub> sorption process heat balance in flow system with stationary activated coke bed. I designed and constructed adiabatic flow reactor, considered as unique and original apparatus. Despite non-stationary character of the process, I managed to determine empirically the heat of SO<sub>2</sub> adsorption [12]. Thermal effect of SO<sub>2</sub> sorption process is comparable to enthalpy of sulfuric acid formation.
  - On the basis of chemical and flow similarity criterion, I determined experimental conditions for adsorption process scale up of SO<sub>2</sub> adsorbent. I proved empirically that direct test results transfer from small to larger scale is well-grounded [13].
- c) Research on catalytic nitrogen oxides reduction on activated carbons using ammonia were based on cognitive and technological work:

- During preliminary tests of nitrogen oxides reduction on activated carbons using ammonia, I proved that it is a contact process in which activated coke is a catalyst [14]. Reduction process runs within the temperature range of 120-180°C, which is characteristic feature distinguishing it from standard SCR process. I proved poor sorption of NO on the surface of activated coke, however easy and efficient one in the presence of ammonia. Long term of non-stationary work (from 2 to 15 hours, depending on parameters of the process) is characteristic for reactor with stationary bed of activated coke [15]. Complex research on nitrogen oxides reduction enabled determination of various parameters influencing their removal efficiency. I studied influence of: contact time (height of the adsorbent bed), temperature as well as concentration of NO, NH<sub>3</sub>, O<sub>2</sub> and H<sub>2</sub>O on reduction level. Test results were described and defined by series of equations of three variables [16].
- On the basis of research on NO reduction using ammonia, I proved that in the temperature above 100°C process runs in kinetic area and it's apparent activation energy reaches 30 kJ/mol [17]. On the basis of experimental data, I developed two kinetic models of NO<sub>x</sub> reduction using ammonia. At first I described the process using standard homogeneous model [18], however better results were obtained while treating reduction as heterogeneous process and elaborating kinetic equation using Young-Hougen model [19].
- I experimented on adsorption process scale up (enlarging of NO<sub>x</sub> adsorber) analogically to SO<sub>2</sub> sorption. I proved that direct test results transfer from small to larger scale is well-grounded [20]. Furthermore using adiabatic flow reactor developed while studying SO<sub>2</sub> sorption, I determined thermal effect of NO<sub>x</sub> reduction using ammonia, which was crucial for process mechanism consideration.

d) Research on catalytic reduction of nitrogen oxides on activated coke using hydrocarbons.

Nature of these research was innovative and during them I was facing the implementation of reduction of nitrogen oxides on activated coke using hydrocarbons (HC-SCR method). The main purpose of that solution was to lower the costs of nitrogen oxides removal through replacement of quite expensive ammonia with less expensive organic reducing agents. I would be even more attractive if low temperature of process could be maintained because of its crucial influence on NO<sub>x</sub> reduction using activated cokes.

- At the beginning I tested NO reduction on commercial activated coke AKP-5 using methane [21]. Unfortunately, NO reduction within the temperature range up to 300°C

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did not proceed, while in 400°C main reducing agent was coal matrix of activated coke.

- Not before 600°C, the reducing agent was methane. I proved that reactivity of organic reducing agent is growing along with the length of hydrocarbons chain [22]. In all cases, minimum temperature of NO reduction was 300°C. Along with temperature rise, nitrogen oxides reduction was improving, to finally become totally removed in 600°C and contact time of 12 s.
- In order to increase activated coke reactivity using technology HC-SCR, I received two kinds of catalysts which activated coke as a matrix. These were catalysts based on precious metals and transition metals. The highest extent of reaction of NO<sub>x</sub> was received on AC/Pt catalyst, however because of formation of vast amount of dinitrogen monoxide, especially in low temperatures of the process, AC/Pt catalyst was rejected from further tests.
- Further tests of HC-SCR process I conducted using more active catalysts received from Nickel (AC/Ni), Cobalt (AC/Co), Iron (AC/Fe) and mixture of propane and butane as a reducing agent. On the basis of research of NO<sub>x</sub> kinetic reduction on specified reducers as well as Young-Hougen model, I developed HC-SCR reduction kinetic models on catalysts C/Ni and C/Co [23, 24]. I described kinetics of nitrogen oxides reduction using mixture of propane and butane and AC/Fe catalyst, by means of neural network [25]. Developed neural network enables precise prediction of nitrogen oxides reduction level within the range of tested parameters.

Despite promising results of tested process, practical use of HC-SCR method for flue gas cleaning has various limitations. First of all, NO<sub>x</sub> reduction using hydrocarbons runs in higher temperatures than expected. Second of all, in low temperatures coal matrix became competitive reducing agent to hydrocarbons, moreover reaching high yield of nitrogen oxides conversion needed large excess of hydrocarbons.

e) Research on adsorptive removal of mercury and its compounds from industrial flue gases.

This is the next stage of research on complex flue gas cleaning using coal materials. Novelty in science and technology were coal-based sorbents for mercury removal received from waste tires. Practical application of that kind of sorbent would solve, not only the problem of waste tires management, but also the problem of mercury removal from flue gases. Premise for that solution is high amount of sulfur (up to 5 %) in chars from rubber wastes. While working on this subject I conducted various of research works, as follows:

- I studied mercury and its compounds removal process using commercial, AKP type activate cokes, used in wastes incineration plants in Poland [26, 27]. To meet the needs of the research I elaborated methodology of mercury analysis in gaseous phase, called „gold-trap”. I proved high yield of mercury vapor removal using activated cokes AKP, in dynamic conditions, even in the temperature of 160°C. Application of 0,2 m activated coke bed, gives total mercury removal from flue gases within 3 hours, even if mercury concentration in flue gas is significantly high. In order to describe received results I used function with 5 parameters, that enables calculation of mercury content in gaseous and solid phase. These parameters can be used for project design purpose.
- I tested mercury removal process based on granular, wastes chars received from thermal processing of rubber wastes (waste tires) [28]. Two types of chars were tested: first of them was received from rotary kiln and second of them was formed in

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stationary bed retort. Laboratory tests were conducted in cooperation with Institute for Chemical Processing of Coal, Zabrze. Test results of both chars revealed high yield of mercury removal and it was comparable to commercial activate cokes AKP. I found improvement of mercury vapor removal efficiency with the temperature, especially within the temperature range of 80-120°C. Unfortunately both chars had poor mechanical strength, which limits their use in moving bed of adsorbent.

- Another research stage was preparation of waste rubber-based granular sorbents. In cooperation with Institute for Chemical Processing of Coal, Zabrze, I developed methodology of char granulation, using various bonding agents, like: tar, molasses or single-stage resin. Granulated products were subjected to carbonization without oxygen presence and received products were tested at an angle of mercury removal from gaseous phase. The best compromise between adsorptive properties and mercury removal efficiency was granulated product received from molasses. Unfortunately poor mechanical strength limits its use. Granulated product received from single-stage resin had highest mechanical strength, but its adsorptive properties worse than other products. In order to improve adsorptive properties of above-mentioned granulated products their activation with steam was performed. Activation process increased surface area along with mercury absorbing capacity of activated granulated products. Optimal parameters of activation were established. Activated granulated products based on single-stage resin and powdery char from rubber wastes were selected to be more perspective adsorbents. Their adsorptive properties are comparable to commercial activated coke- AKP 5. Method of granulated adsorbents preparation became patent [29].

Obtained research results proved that, it is possible to use waste material- char after thermal processing of wasted car tires, to produce low-cost adsorbents for mercury removal from flue gases.

- f) Research on regeneration of used activated cokes and determination of fluctuation of their characteristic parameters.
- I studied SO<sub>2</sub> thermal desorption from used activated coke in various temperatures [30] and I proved that within 2 hours and in the temperature of 450°C, level of SO<sub>2</sub> desorption exceeded 99%. Use of inert gas passing through activated coke bed decreased desorption temperature to 400°C. During the process of thermal regeneration I observed mass loss of activated coke, which was proportional to amount of SO<sub>2</sub> released during desorption. It is unfavorable phenomenon coming from reduction of sulfur compounds adsorbed by coal material of activated coke.
  - I tested mercury and its compound desorption from the surface of used activated coke. Research tests concerned Hg<sup>0</sup> desorption [31, 32] as well as its volatile compounds: HgCl<sub>2</sub> [33] and HgJ<sub>2</sub> [34]. Study of desorption kinetics proved total desorption of Hg<sup>0</sup> from the surface of activated coke, in the temperature of 400°C, after 2 hours. Total desorption of mercury compounds takes place in lower temperature (350°C for HgCl<sub>2</sub> and 300°C in case of HgJ<sub>2</sub>). Obtained results proved that mercury and its compounds could be totally removed from the surface of activated coke during thermal desorption of SO<sub>2</sub>.
  - I have studied the alternative method for sorbent regeneration using wet method [35]. For chemical leaching of SO<sub>2</sub> sorption products water and diluted solutions of sulfuric acid

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was used. Chemical leaching in 4 reactors cascade with stationary bed enabled to receive final regeneration yield up to 90%. Unfortunately one of the regeneration products is a highly contaminated solution of 25% sulfuric acid, which makes its management difficult. The benefit of wet method of regeneration is lack of chemical use of sorbent, which takes place during thermal desorption.

Relevant feature of conducting of thermal desorption is chemical deactivation of activated coke because of its „burn-up“ within reduction of adsorbed sulfur compounds by means of elemental carbon. This brings changes to porous structure of activated coke and influences its adsorptive and catalytic parameters. I tested changes of characteristic parameters of two kinds of activated coke in SO<sub>2</sub> sorption cyclic process- thermal regeneration [36]. I proved that successive cycles bring gradual loss on mass connected with changes of porous structure- growing the surface area and micro-pore volume. Described changes went along with unfavorable lowering of the ignition temperature [37] as well as loss on mechanical strength and bulk density. In further cycles adsorption properties of SO<sub>2</sub> and mercury vapors are improving. Yield of ammonia NO<sub>x</sub> reduction does not depend on sorption-regeneration cycles. It should be underlined that research concerning changes of sorption and catalytic properties were never published before.

Test results presented in publication cycle create physical and technological basis of application of selected polish activated cokes in technology of adsorptive industrial flue gas cleaning systems. Broad research on this subject were conducted and they considered:

- SO<sub>2</sub> sorption, NO<sub>x</sub> catalytic reduction using ammonia and two methods of waste activated cokes regeneration;
- kinetics of particular cleaning process, in which large amount of kinetic models were elaborated;
- establishing optimal technological parameters of particular cleaning processes, as well as parameters of test results application in larger scale;
- acknowledgment of possibility of polish activated cokes application in cyclic sorption-regeneration process and establishing the influence of process periodicity on physical and chemical, sorption and catalytic changes of their characteristic parameters.

Novelty in science in presented cycle of publications was a trial of HC-SCR method application in nitrogen oxides reduction, using activated cokes and activated coke- based catalysts. Industrial implementation of that solution would give significant savings thanks to application of cheaper reducing agent and process temperature subsidence.

Detailed description of mercury vapor adsorption process on the surface of industrial activated cokes- AKP type, as well as determination of optimal mercury removal parameters, was extremely valuable. Novelty in science is presented trial of low-cost adsorbents (received from char of waste rubber thermal processing) application in mercury removal from flue gases.

Research results presented as a cycle of publications, concerning: polish activated cokes parameters, as well as particular processes of technology of adsorptive and catalytic industrial flue gas cleaning, are scientific and research basis for industrial implementation of this technology.

## **5. Description of others research and scientific achievements**

Main scope of my research interest is application of coal-based adsorbents for industrial flue gases cleaning systems. Complex approach to that matter is the base of my habilitation

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(post-doctoral dissertation) procedure and it is expressed through list of my scientific publication presented in previous chapter. Secondary scope of my research interest are related to environment protection and chemical technology, especially gas phase cleaning. Above mentioned scope of interest can be divided in three main fields:

- reduction of mercury and it's compounds emission to the atmosphere;
- reduction of carbon dioxide to the atmosphere;
- general matters concerning chemical technology.

5.1. Research and scientific achievements in field of reduction of mercury and it's compounds emission to the atmosphere.

Reduction of mercury and it's compounds emission to the atmosphere is relevant scientific issue concerning variety of Polish and European legislation acts, e.g. "IED Directive" in force from 2010, "BAT Conclusions" in force from 2017, or finally "Minamata Convention on Mercury" signed by Poland in 2014. First steps of my work in field of reduction of mercury and it's compounds emission to the atmosphere was taken in 2005, through scientific grant KBN "Coal-based sorbents for mercury removal from industrial flue gases, received from waste tires". Project was leaded by me since 2005 to 2008 in cooperation with Institute for Chemical Processing of Coal in Zabrze, Poland. Complex description of work package of this project is part of my research achievements presented in previous chapter. Despite already mentioned achievements this project was also a base for elaboration of analytical techniques for determination of mercury content in gas phase (I set to work a mercury on-line analyzer which was one of the first in Poland) and creation of unique research laboratory for mercury and it's compound removal from industrial flue gases, in Poland. Know-how which I build during that project was used in 2008, in my expertise ordered by IChPW "Elaboration of methodology of sample preparation and determination of mercury content in solid, liquid and gaseous samples".

In 2013 I participated in engagement of, one of the first in Europe, Integrated Analytical System Tekran 3300, which enables on-line analysis of mercury concentration (along with speciation of mercury gaseous forms) in power plants flue gases. I completed special training concerning maintenance of Tekran 3300 and conducting of analysis, which was confirmed by producer's certificate.

From 2011 to 2015 I participated in Work Package 4 of international project CoalGas „*Development of a Coal Gasification Technology for High Efficiency Fuels and Power Production*”, financed by TAURON Polska Energia S.A. and KIC InnoEnergy SE. Within the framework of Work Package 4 "Monitoring and reduction of mercury emission during coal combustion and gasification process" I participated in industrial mercury emission testing on Power Plant Łaziska and Power Plant Jaworzno II and developed approach to determination of mercury balance in selected boilers and gas cleaning systems e. g. FGD, IOS. Data collected during mercury testing (measurements of mercury concentration in combusted fuel and all waste products from power production allowed to create mercury balance for power plants) leded to elaboration of mercury cycle model on tested power plants. Moreover along CoalGas I also participated in part of the project conducted by AGH Kraków and took measurements for mercury speciation in flue gases using Tekran 3300 Analytical System. Measurements took place on Pilot Scale Demo Installation for mercury monitoring and reduction of mercury emission form pulverized-fuel boiler, constructed on Łaziska Power Plant.

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From 2013 to 2016 I was a member of a team preparing the draft for financing the project BazaHg "Elaboration of database of mercury content in domestic coals and guidelines for technologies of mercury emission reduction concerning benchmarks for domestic index of mercury emission levels". Project was conducted within the framework of II Applied Research Program NCBiR from 2013 to 2016, by scientific consortium: GIG Katowice, AGH Kraków, IChPW Zabrze and Technical University Częstochowa. As a manager of this project in IChPW I developed database of characteristic parameters of Polish lignites, with special attention to mercury content. I was responsible for: determination of fluctuation of mercury concentration in post-flotation wastes during their long term deposition and testing of mercury migration along the oil agglomeration of post- flotation sediments. Above-mentioned research was based on my innovation idea.

In 2017-2018 I participated in elaboration of feasibility study for lignite-based activated carbon production for mercury removal from flue gas, on Bełchatów Power Plant. It was ordered by IE Warszawa and PGE GiEK Bełchatów. I participated in research concerning elaboration of lignite-based activated carbon production concept in Pilot Scale IChPW, in circulating fluidized-bed reactor and testing its adsorption parameters.

I participated in tests of mercury emission and balance in Power Plant Żerań (ordered by Elewator Poland in 2017) and as a team leader in Power Plant Koźienice (ordered by IEM GmbH Germany in 2018).

All above-mentioned tests was realized by me within the frameworks of 1 international and 2 domestic projects from KBN and NCBiR, 5 statutory works in cooperation with Silesian University of Technology and IChPW Zabrze and few commercial tests and expertise. Results of my work was promoted through my scientific publication, presented on domestic and international conferences.

## 5.2. Scientific and research achievements concerning reduction of carbon dioxide to the atmosphere

CCS (Carbon Capture and Storage) and its management CCU (Carbon Capture and Utilization) is my second main field of interests. This work is relevant scientific issue concerning European legislation acts on Greenhouse Gases e.g. Directive 2003/87/EC.

First steps of my work in field of CO<sub>2</sub> capture from gas phase was "Regeneration of used activated carbons and coal-based sorbents" conducted in 2001 as a statutory work for Silesian University of Technology. Along the work I tested thermal regeneration of coal-based sorbent SDW, used for adsorptive carbon dioxide removal from the air. Test results were easily implemented to regeneration of sorbent used for protection of water-glass containers, in Baildon Steel Plant in Katowice. Test results were published through publications.

Another work in field of CCU was project HTRPL " Research and development of high-temperature reactors for industry" conducted within the framework of project "Technologies supporting development of safe nuclear power production". Project HTRPL was conducted from 2012 to 2016 in broad scientific consortium: AGH Kraków, GIG Katowice, INSC Puławy, IChPW Zabrze, NCBJ Otwock, Prochem SA, Tauron, Univeristy Warszawa, KGHM S.A., Silesian University of Technology and Pomeranian Special Economic Zone. I was a team leader of research works in Work Package "Rational use of CO<sub>2</sub> with simultaneously use of redundancy heat from HTR reactors". Main results of this research was selection of best available technique with high energy demand and using carbon dioxide

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as a feedstock. During that work I analyzed three technologies: dry coal gasification, reforming of methane using carbon dioxide and soda production using Solvay's method. Based on technological and economic analysis I selected dry reforming of methane as best available technique using heat from HTR. In cooperation with M. Motak PhD from AGH Kraków I was able to elaborate new catalyst for conversion of methane with carbon dioxide based on hydrotalkit. Based on large scale tests I evaluated optimal parameters of catalytic conversion process and elaborated project guidelines for dry methane reforming process.

I participate in three work packages (as a leader of two of them) of project OPTYSODA conducted since 2016 by CIECH Soda Polska SA, within the framework of Sector Program INNOCHEM (POIR). The main purpose of the project is commercialization of new technologies of residual carbon dioxide capture from flue gases using Solvay's process. Within the framework of work package concerning ammonia CO<sub>2</sub> capture method, scientific group of specialist from IChPW under my direction, thoroughly tested adsorption of CO<sub>2</sub> in waste ammonia condensates. In cooperation with design office Sodaconsult, Kraków, I designed pilot scale installation for ammonia CO<sub>2</sub> capture, with capacity of 7000 m<sup>3</sup>/h. A present (2019) installation designed by me is being built on Soda Factory in Inowrocław under supervision of IChPW, Zabrze. Deadline for testing on that installation is 2020. Second work package concerned technology of ammonia CO<sub>2</sub> capture method and all test were conducted on pilot scale installation for ammonia CO<sub>2</sub> capture, with capacity of 100 m<sup>3</sup>/h. Test results were the ground for development of innovative technology concept of CO<sub>2</sub> (concentration of 40 % in residual gases) capture during Solvay's process. Within the framework of third work package of project OPTYSODA research on thermal regeneration of ammonia condensate was conducted. Under my direction, large scale desorption installation with capacity of 50 kg/h was designed and built. In cooperation with design office Sodaconsult, pilot scale installation for regeneration will be designed and built on Soda Factory in Inowrocław, based on my research work from 2019. Within the framework of all work packages of project OPTYSODA 6 home and foreign patents were issued. Test results were presented in 2 scientific journals from list A.

Currently I am participating in two international projects co-funded by Tauron Wytwarzanie i KIC InnoEnergy SE. These are projects CO2SNG „*Energy storage by production of SNG z CO<sub>2</sub> – methanation system of CO<sub>2</sub> received from flue gases*” as well as project POLYGEN “*Poly-generation system of biomass and solid recovered fuel gasification*”. Projects CO2SNG is conducted since 2014 by international consortium: IChPW, Tauron Wytwarzanie, CEA (France), Atmosstat (France), Rafako, Exergon, WT&T. The aim of the project is development of technology and building a pilot scale installation for synthetic natural gas (SNG) production. Feedstock for this technology is carbon dioxide received from flue gases using ammonia adsorption method, according to IChPW technology as well as hydrogen electrolytically produced by means of redundant electric energy from renewable sources. During methanation process feedstocks will be turned into eco-fuel – synthetic natural gas. Within the project pilot scale installation, on Łaziska Power Plant, was built.

In 2018 scientific group of specialist from IChPW under my direction, set this installation to work and started process testing. After completing all tests in 2019, commercialization of developed technology is planned. Projects POLYGENE is conducted since 2016 by international consortium: IChPW, Tauron Wytwarzanie, CEA (France), Atmosstat (France), Rafako, Exergon, Eqttec Iberia (Spain). The aim of the project is to build pilot scale installation for receiving synthetic natural gas (SNG) from waste fuels and carbon dioxide received from flue gases. Waste fuels will be gasified using Eqttec Iberia (Spain) technology. Gas received

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after upgrading process (IChPW) will be processed to synthetic natural gas (SNG) using methanation process. During methanation process, carbon monoxide received from flue gases by means of ammonia method (IChPW), will be used. Currently design stage is over, that is why in 2019 pilot scale installation will be built on Łaziska Power Plant. Scientific group of specialist from Gas Cleaning Group IChPW Zabrze, under my direction, after starting up the installation on pilot scale, will carry out various of tests. When project reach the end commercialization of it is planned.

Since 2013 I am technical expert GHG for TÜV SÜD company in Chorzów in fields of: inorganic chemical technology, fuel combustion, coke production and metallurgy of ferrous and non-ferrous metals, production of building material e.g. Along cooperation I was technical adviser GHG during auditing of procedure of annual CO<sub>2</sub> emission balance for production plant of CIECH, Euroglas ad others.

In 2017 I was main author of expertise "*Evaluation of CPPE CO<sub>2</sub> reduction technology in flue gases using adsorption method*". Based on inspection and review of pilot scale installation for CO<sub>2</sub> capture in clinker production plant Cimalux in Luxemburg and after analysis of Cimalux know-how, I estimated their technology for CO<sub>2</sub> removal at an angle of possible application in Poland. Above mentioned research were conducted within the framework of 2 international projects, 2 NCBiR project (one is Strategic Project), statutory works of Silesian University of Technology and IChPW Zabrze, as well as commercial works and expertises. Results of my work was promoted through my scientific publication, presented on conferences and 7 issued patents.

### 5.3. Others scientific and research achievements

To 2012 I participated in various research works conducted on Silesian University of Technology and since 2012 in IChPW Zabrze. My work did not concern only theoretical approach to technology calculation but also various scale experiments in chemical processing technologies and environment protection. The most relevant scope of my research work is:

- thermodynamic analysis of selected chemical technology processes;
- stoichiometric and thermodynamic analysis of receiving of titanium nitrite;
- improvement of unit process in inorganic chemical technology;
- research on sorbents for adsorption of ammonia from gas phase;
- development of laboratory analytical techniques in IChPW;
- elaboration of optimization model for coking plant water treatment system;

I was an author of many expertises ordered by industry or scientific partners:

- Institute of Carbochemistry PAN, Gliwice – development of methodology of activated carbons testing;
- Jasło Refinery – measurements of organic contaminants from containers for hydrocarbons;
- Gryfskand, Hajnówka – testing of activated carbons and cokes;
- Opole Power Plant – anticorrosive protection for nuzzle of IOS adsorber;
- Hyundai Steel Corporation – matching activated cokes;
- IChPW, Zabrze – methodology for mercury analysis;
- CIECH Soda Polska SA – technological and economic analysis;
- Tauron Wytwarzanie S.A. – implementation of CO<sub>2</sub>SNG technology.

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All above-mentioned works was conducted within the framework of 6 research and scientific works for Silesian University of Technology and IChPW as well as 6 expertizes for individual orderers.

## 6. Summary of scientific, didactic and organization activity

### 6.1. Summary of scientific activity

Achievements in field of publications of research work:

- I published 17 papers in journals stated in JCR base (for 6 of them I was the only author). Total impact factor for those papers is IF= 11,0. Before my PhD I was an author of 3 papers in journals stated in JCR base (IF= 0,7).
- I am the only author of publication in conference materials reported by WOS.
- I published 29 papers in journals not stated in JCR base (16 of them in English). I was the only author for 5 of them, and co-author of 24 papers. Only one of my papers was published before my PhD.
- I published 24 chapters in scientific monographs and 2 of them in English (I was the only author for 8 of them). 17 of my papers was published in international scientific conference materials (for 9 of them I was the only author)
- I participated in 74 domestic and foreign scientific conferences, where I presented 66 of my papers (14 on international conferences), 9 communications and one section presentation.
- I am coauthor of 3 patents and 7 patent application (3 of them in UE).

Achievements in field of implementation of research work:

- I participated in 3 international projects co-financed by KIC InnoEnergy.
- I was a leader executor in 4 long term (3 years) grants financed by KBN.
- I conducted grant (3 years) financed by MNiI.
- I was a leader of Work Package in IChPW in two projects conducted in scientific consortium (Project HTRPL- 3 years, project BazaHg- 3 years within the framework of PBS); Both projects were funded by NCBiR.
- I conduct 3 scientific works ordered by CIECH Soda Polska, in INNOCHEM project co-financed by NCBiR. I am a leader in two of them.
- I was responsible for one of the work package of Inteligentna Koksownia (project POIG financed by NCBiR);
- I realized 9 scientific and research works ordered by various orderers (I was a leader for 2 of works).
- I realized 9 expertise opinions for the industry (for 6 of them a I was the only author).
- I realized 11 financial works based on satutory resources from Silesian University of Technology and IChPW (I was a leader in 7 of them, and twice a leader of work packages).

In 1995 I was awarded by Chancellor of Silesian University of Technology for my PHD dissertation.

Quantitative expression of my scientific achievements:

No	Achievements	Before PhD	After PhD	Total
1.	Publications in journals stated in JCR	3	14	17
2	Publications from MNiSzW list not stated in JCR	1	28	29
3	Publications in conference materials stated in JCR	0	2	2
4	Patents granted	0	3	3
5	Patent application	0	7	7
6	Chapters in review monograph, total: - along with publication in English	0 0	24 2	24 2
7	Presentation on scientific conference, total: - presentation on international conferences - presentation on domestic conferences - short presentation on domestic conferences	17 0 12 0	91 14 40 9	108 14 52 9
8	Publication in conference material, in English	0	17	17
9	Participation in projects KBN, MNiI, NCBiR: - as a leader - as a main contractor	2 0 2	7 3 3	9 3 5
10	Participation in international projects	0	3	3
11	Significant commercial work for industry: - along with cofinanced by NCBiR	4 0	9 3	13 3
12	Expert opinion	1	8	9
13	Statutory work	3	8	11
14	Achievements – total according to MNiSzW criteria	53	823	876

## 6.2. Summary of didactic activity

From 1989 and 2016 I was an academic teacher on Department of Chemistry of Silesian University of Technology in Gliwice. I had regular lectures and classes with students in field of chemical technology and chemical engineering on Silesian University of Technology as well as on branch facility of Silesian University of Technology, situated in Dąbrowa Górnicza. I had lectures and classes on externistic studies of Silesian University of Technology in Gliwice. Subject area of my classes was: chemical and processing thermodynamics, chemical reactors engineering, chemical technology and environment protection. I prepared and leader classes of 8 subject individually and all of them ended with an examination. Despite my didactic activity I have managed to elaborate 10 new research work place along with technical instruction and procedure to carry out laboratory works for students. All technical instruction and infrastructure was used to carry out laboratory works for different, 11 subjects. During my didactic activity I was also responsible for leading calculation practices for 8 technological subjects an temporary experimental works in laboratory. I was scientific support and guide for 9 dissertation of master's degree (M.Sc) and promotor of 37 dissertation of master's degree (M.Sc) and 7 engineer's degree. All works were not only theoretical but also experimental. I was also a reviewer of 98 master's and engineer's degrees.



### 6.3. Summary of organizational activity

Since 1989, I am a member of Society of Engineers and Technicians of Chemical Industry. From 1997 to 2002 and from 2010 to 2012 I was chairman of SITPChem society on Silesian University of Technology, and was rewarded as a honored member of SITPChem society (2002). From 2002 to 2012 I was responsible for organization of annual competition for the best dissertation of master's degree (M.Sc) on Silesian University of Technology.

In 1995 I was co-organizer of session promoting Department of Chemistry during celebration of 50th anniversary of establishment of Silesian University of Technology. Since 1996 I organized scientific seminars promoting Department of Chemistry of Silesian University of Technology among high school students from Silesia. From 1996 to 2012 I organized scientific seminars in the Institute/Department of Chemistry, Inorganic Technologies and Electrochemistry. For many years I was a guide and took care of many associated students group studying on the Department of Chemistry.

Since 2015 I am a Head of Gas Cleaning Team on the Institute for Chemical Processing of Coal in Zabrze.

*Krzysztof Jastyk*

*KJA*