Air Purification in Highly-Urbanized Areas with Use TiO$_2$: New Approach to Design the Urban Public Space to Benefit Human Condition

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Abstract. This paper deals with the possibilities of architectural design to benefit human condition, which encompasses physical well-being, environmental quality of life in highly-urbanized areas. Nowadays, the urban pollution is rising on a global scale. The paper is focused on a new possibility to resolve the problem of air purification in big cities by advanced architectural design public use spaces in the urban environment. The first part of the paper depicts possible usage of Titanium dioxide (TiO$_2$) technology - nanoparticles of TiO$_2$ as a building materials component. These components are the latest findings in the field of nanomaterials development, and their effectiveness due to the usage of the photocatalysis, which depends on eliminating various atmospheric pollutants and especially clearing the atmosphere from nitrogen oxides. These components together with calcium carbonate to neutralize any acidic gasses that may be adsorbed. Photoactive construction materials are mainly activated under UV light irradiation. The second part presents the results of the research program Climate Change Adapted Architecture and Building Structures which has been conducted by Krystyna Januszkiewicz (the Faculty of Civil Engineering and Architecture for a few years at West Pomeranian University of Technology (WPUT) in Szczecin. The presented designs were developed with co-operation, Magdalena Janus and Kamila Bogacz (Institute of Chemical and Environmental Engineering) as applications samples of titanium dioxide technology (photocatalytic active building materials) in the urban space. In conclusion, the paper emphasizes the usage of titanium technology, as a construction materials component such as concrete and gypsum or a component of active membrane fabrics opens a new way in architecture and structure designing in the urban public space. This is indispensable to improve citizens' health and to clear the atmosphere from nitrogen oxides or the volatile organic compounds and serves also as the basis to newly-built communities.

1. Introduction

Air quality in major cities across the globe is taking a hit to alarming levels due to large scale industrialization without respecting emission norms. Air pollution is a worldwide problem. About 6.5 million people die every year due to air pollution according to the UN and 92 percent of people in the world are exposed to so poor air quality so poor, it poses a major health risk [1]. Since 2000, a daily air pollution index (API) and air quality levels are available in many cities. Over the past decade, scientists have been uncovering the short- and long-term health impacts of ingesting the pollution in big cities, in order to try to tackle the growing mortality rate. Inhaling toxic materials cause an inflammatory reaction in human body. Gases such as sulphur and nitrogen dioxide have been heavily
linked to respiratory and cardiovascular illnesses, while ozone, formed when sunlight reacts with a cocktail of other gaseous pollutants, is toxic in the lower atmosphere [2]. Levels of nitrogen dioxide continue to soar in big European cities, regularly reaching more than three and half times European Union limits [3]. The following study is an application of the experimental approach to architectural and urban design in recently re-opened discussion on possibility and advisability of creating a systemic solution to resolve the problem of air purification in big cities. It is—research for new solutions through implementation of today’s advanced technologies and materials. Envisioning "City Oasis" deals with the problem using experimental gypsum plasters and cement or membrane fabrics components and added with titanium dioxide in designing architectural objects dedicated de-polluting effect of sulphur, nitrogen and carbon dioxide in the lower atmosphere of polluted urban areas.

2. Global problem air purification in big cities

Air quality in big cities is the result of a complex interaction between natural and anthropogenic environmental conditions. Air pollution in highly-urbanized areas is a serious environmental problem of concern all over the world. The rapid urbanization and growing number of megacities and urban complexes require the new types of research and services that make the best use of science and available technology.

Ambient concentrations of PM$_{2.5}$ and PM$_{10}$ are of concern with respect to effects on human health and environment. Increased levels of mortality and morbidity have been associated with respirable Ambient concentrations of PM$_{2.5}$ and PM$_{10}$ are of concern with respect to effects on human health and environment. Increased levels of mortality and morbidity have been associated with respirable particulate air pollution. Several statistical tools and models have been used to determine the sources of PM all around the world. Elemental composition of PM is the input data of these tools and models. The studies showed that composition and sources of PM strongly depend on the location, traffic load, fossil fuel utilization and industrial activities at sampling sites. The metropolitan areas are the most important developing urban areas with serious air pollution problems [3]. Chemical and environmental engineers, architects and structural engineers, urban planners and health scientists, physical scientists are starting to answer specific questions about how cities and the urban environment will interact in the face of global problem of air purification.

Since January 2018, the world’s largest Air Purifier is on the trial in Xi’an, the capital of China's central Shaanxi province (figure 1a-b). The 100-meter-tall air purification tower has significantly improved the city air quality. According to researchers from the Institute of Earth Environment at the Chinese Academy of Sciences, the tower has managed to produce more than 10 million cubic meters of clean air per day. In the 10 square kilometers observed area of the city, smog ratings have been reduced to moderate levels. To clean the air, polluted smog is drawn in through a series of greenhouses surrounding the base of the tower and heated by the solar energy. This newly hot air then rises up the tower through multiple scrubbing filters before it is released back into the atmosphere. This technology called "solar-assisted large-scale cleaning system" (SALSCS) was first developed by David Y.H. Pui's team at the University of Minnesota in 2014 [4]. This method allows the air to be
cleaned using relatively minimal electric power. The Xi’an smog tower project was launched in 2015 as a trial version of a much larger system the research team hopes will be implemented in other Chinese cities in the near future. The full-sized tower would measure 500 meters tall and 200 meters in diameter, with greenhouses covering nearly 30 square kilometers. This system is hoped to be powerful enough to purify the majority of the air within a small city. The quiet, energy-efficient air purifying towers are a potential cost-efficient solution to the China's smog problem [5]. However, building many of them to cover a large and dense city could be impractical, considering how much space they require, the one in Xian having been built in one of the city's outer industrial zones. Nonetheless, the towers represent China's continued efforts to aggressively address its air quality problems. The next purification huge towers are planning in Taiwan (figure 1c). This is a second-generation version equipped with LED advertisements is designed to be used in urban centers to serve also as the basis of newly-built communities.

**Figure 2a-b-c.** Daan Roosegaarde, Bob Ursem, Smog Free Tower - portable air-purifier, 2016

Since 2016, a Dutch designer Daan Roosegaarde and his team in collaboration with ENS Europe and professor Bob Ursem are testing experimental air-purifier called Smog Free Tower (figure 2a-b-c) that is installed initially in Rotterdam, and then will be traveled from city to city, demonstrating a possible solution to fighting air pollution. They developed a large air ioniser, some 7 meters high, which is touted to be able to clean 30,000 cubic meters of air per hour, with power consumption 1700 watts. An electrode will send positive ions into the air. These ions will attach themselves to fine dust particles. A negatively charged surface -the counter electrode- will then draw the positive ions in, together with the fine dust particles. This is a portable version of technology that is already used in hospitals [6].

Trees are natural filters and a natural cleaner air. Taking this into account, designers Mario Caceres and Cristian Canonico have designed a set of street-sculpture air-filtering trees for an action "the SHIFboston urban intervention contest" in October 2010. Called TREEPODS, the designs harnesses biomimicry to efficiently emulate the carbon filtration qualities of trees.

**Figure 3a-b.** Mario Caceres, Cristian Canonico, "Treepods" in Boston’s urban space, 2010
Boston Treepods is an urban intervention which contains a system that is capable of removing carbon dioxide from the air and releasing oxygen using a carbon dioxide removal process called “humidity swing”. In addition to cleaning the air, the Treepods will also generate energy with solar energy panels while harvesting kinetic energy through an interactive seesaw that visitors can play with at the Treepod's base. When a person plays on the see saw, the power display explains the Treepod's de-carbonization process. The solar panels and the kinetic energy station are used to power the air filtration process, as well as interior lighting. The Treepods are made entirely of recycled/recyclable plastic from drink bottles with using titanium dioxide as a component. Based not only on TiO$_2$ proprieties, but also on the human lung, the design of the “branches” feature multiple contact points that serve as tiny CO$_2$ filters. At night, the Treepods light up in an array of eye-catching colors. Interestingly, the Treepods have been compared to “urban furniture”: sleek yet functional design pieces that would fit into any urban environment [7].

Scientists at the University of Engineering and Technology (UTEC) in Peru have invented reactive billboards. According to the team, a single billboard can do the work of 1,200 trees, purifying 100,000 cubic meters of air daily in crowded cities. The experimental version has installed its first air-purifying billboard near a construction zone in Lima, a city that is famous for having the worst air quality in all of South America. The billboard works by combining polluted air with water, using basic thermodynamic principles to actively dissolve the pollutants (such as bacteria, dust and germs) in water to release fresh air [8].
building. On the basis of the cement, an Italian construction firm has developed a 'biodynamic' mortar building material that is able to remove pollutants from the air automatically. The Palazzo Italia used more than 2,200 tons of the new cement, which was cast into panels to cover much of the exterior and some of the interior of the distinctive building (figure 5). The mortar, which is made from recycled scraps of marble and left over aggregate, absorbs nitrogen oxide and sulphur pollution and converts it into harmless salts. It uses a titanium catalyst that is activated by ultraviolet light to drive the chemical reaction. The salts then wash off the walls when it rains [9].

The examples presented above are only some of the latest results of the multi-disciplinary research to eliminate polluted air in the public use areas in the city. Digital technology has opened up new opportunities in various fields. Designers and scientists around the world believe that art has a role to play in shifting people's ideas about how pollution can be part of the solution.

3. Air purification Global problem air purification with using titanium dioxide TiO₂
The most promising and innovative strategy for the building envelope of nowadays and tomorrow is based on a dynamic, active and integrated solution, able to purify polluted air and optimize the environmental performance, integrating active elements and systems, exploiting energy from renewable source. Considerable efforts in research and development are necessary to achieve a sustainable and effective building materials with a dynamic behaviour [10].

The research results, which were conducted in the last decade using titanium dioxide as additive to such building materials as a gypsum and cement, indicated their properties, which should be dedicated to the high urbanized cities [11]. Using titanium dioxide as additive to these materials gives them self-cleaning, antibacterial and antifungal properties, moreover it was found that in some cases the mechanical properties are also improved [12]. Recent studies have focused on the development of new methods, such as photocatalysis which, in principle, leads to the complete mineralization of the targeted pollutants. Photocatalytic process proceeds according to the following mechanism: photons are absorbed by TiO₂, which generates electron-hole pairs. In contact with water and oxygen, free radicals (mainly O₂•− and •OH) are generated, which are able to oxidize organic matter to water and carbon dioxide, leaving no other residue [13]. Today, TiO₂ photocatalysis is widely used in a variety of applications and products in the environmental and energy fields, including self-cleaning surfaces, air and water purification systems, sterilization, hydrogen evolution, and photoelectrochemical conversion [14]. Research for new properties of the building materials such as concrete and gypsum are developing also at the West Pomeranian University of Technology in Szczecin. The inquiries have been developed by Magdalena Janus and Kamila Bogacz and their team with the commercial amorphous titania, which was supplied by Grupa Azoty Zakłady Chemiczne „Police” S.A. (Poland), used as a crude material for the synthesis of N and/or C modified TiO₂ photocatalysts [13]. The team of scientists focused on gypsum plasters to which modification of unmodified titanium dioxide TiO₂ is added, by heating it in a tubular furnace in ammonia and carbon dioxide, respectively, to temperatures of 100, 300 and 600 °C. Researchers at the West Pomeranian University of Technology in Szczecin prove that the addition of titanium TiO₂ to the carbon and nitrogen (TiO₂-N, C) increases the photoactivity of the gypsum, which helps in the better degradation of nitrogen dioxide (NO₂). In addition, it has been proved that the photocatalytic addition to the gypsum material increases the compressive strength of this material. This extends the possibilities of using these materials in building structures.

4. Designing and research for clean air places in highly urbanized areas
Last year these issues were undertaken by Krystyna Januszkiwicz (Leader of Digitally Designed Architecture Lab) and faculty member at the WPUT (West Pomeranian University of Technology) in Szczecin. The program combines techniques and strategies of digital parametric modeling with research concerning the behavior of materials and structures.
The main aim of designing research program was to demonstrate new possibilities of application the new light active building materials developed by Magdalena Janus and Kamila Bogacz and their team at the Institute of Chemical and Environmental Engineering WPUT in Szczecin. The product is currently being introduced into a building market. This product meets the criteria of an innovative product used in the building industry by delivering multi-curved shapes and, at the same time, lowering the cost and being environmentally friendly. The gypsum product delivers about 45% of combined energy savings in manufacturing, transportation and installation.

The task was to design a public use architectural object in an area with increased street traffic e.g. the city of Szczecin. There are three visions of "City Oasis", a place where you can stay and spend free time. Each project design treats urban air pollution and improve the air quality. This study redefines an architectural form not as the shape of a material object alone, but as the multitude of effects, the milieu of conditions coded into parametric and computational designs. In this approach the architectural form constitutes the clean of micro-environmental zones within an emergent macro-environmental system that city is. It involves parametric digital design tools, digital and physical form finding, structural analysis and ecological testing techniques. The initial design criteria of the projects differ according to their contexts in the city and the degree of air pollution.

In the first part of the program the main negative and positive factors were defined which are influencing the formation of architectural form in big cities. One of them are various atmospheric pollutants. The impact of these negative factors is constantly increasing in the time of climate change processing. The second part of the research program goes on to attempt to solve the problem through architectural design, which involves the new light active building materials with TiO2 and the latest technology.

5. Results and discussions
The capacity for the new light active building materials for building skin to actively support purifying building function is critical to the future of building envelopes design. The presented proposal of “City Oasis” prepared by the Digitally Designed Architecture Lab (2016-2017) at WPUT in Szczecin shows the possibilities of how to use the active membrane fabric, gypsum plasters and cement composition panels and process them into the friendly urban environment.

5.1. Air-purifying and shading folding device inspired by Nature
The Peace Lilly flowers (Spathiphyllum ‘Mauna Loa’) absorb the pollutants in the air as well as carbon dioxide. Then, the plants then undergo photosynthesis and transform these harmful elements into oxygen (figure 6). Taking this into account, Master Program students have designed a set of street-devices air-purifying and shading umbrella-flowers for outdoor events in the Old Slaughterhouse Culture Center on the Łasztownia Island in Szczecin (figure 7).

Figure 6a-b-c. The Peace Lilly flower - shape study and air purification process diagrams, 2017
The Peace Lilly Flowers Square presents systems which are capable of removing carbon dioxide from the air and releasing oxygen using the titanium dioxide $\text{TiO}_2$ (figure 7). It is possible when the outer layers of membrane fabric are the UV active composition $\text{TiO}_2$ with a flexible polymer substrate. The membrane fabric is a basic material used to forming umbrella-flowers on this square. In addition to their air-cleansing abilities, every umbrella-flowers can collect rainwater to cultivate grass sections on the square. In initial designs the square also included solar energy panels and interactive panels that visitors could play and learn about de-carbonization process. This solar energy generated by day could be use to the might illumination (LED) in order to create a magic place on this island.

5.2. *Envisioning “City Oasis” in downtown Szczecin*

The “City Oasis 1” is located at the busiest place in Szczecin downtown where the annual air quality standards for PM 10 are significantly exceeded. This pavilion is orientated for the sun, wind and smell conditions. It consists of two parts with twin identical free surfaces, but with a different structure (figure 8). ‘Wind-catchers’ integrated within the roof profiles on the southern sides of each semi-open space catch the polluted air and the prevailing winds from the north. It is also expected that both parts of the pavilion will collect rainwater by draining it into a linear drainage system, which will be introduced into the water supply after purification. The semi-envelope consists of supporting bar structure, on which from the outside is fixed faceted fibrobetone sheets with the addition of $\text{TiO}_2$-N. From the inside, on a steel grid with using the shotcrete pressure method - a mixture of photoactive gypsum was distributed to create a shell integrated with the supporting structure. Strategically spatial layering effects are created throughout the pavilion to provide views to the urban context offering transparency between public areas designed as collective zones with clean air for citizens’ to meet and exchange ideas.
The "Oasis 2" on two islands on the Odra River in the geographical center of Szczecin. This is a shell of supporting bar structure with an active environmental surface (figure 9). It was proposed that the
outer surface of this supported structure was covered with modified concretes with photocatalytic activity. The use of 320 panels with a unique shape was predicted. The inner coating consists of the spray coating gypsum with the addition of TiO$_2$-N, C. The pavilion is supposed to purify the air from several nearby traffic crossings connecting the right bank and the left bank of Szczecin. This is a semi-open public space of a recreational and educational nature. The pavilion is also designed in response to the environmental conditions of the Szczecin-Odra-area to save rainwater, minimise energy, and resource consumption.

The presented above envisions of “City Oasis” have provided a conceptual basis and pointed the need for further research on the properties of the new light active building materials such as elasticity, compression, bending and stretching, but also in terms of sensitivity to heat, water, hygroscopicity, shrinkage, frost-resistance, and sunlight, etc.

5.3. Herring Air Purifier Tower for Szczecin Port

The wind tower form located in Szczecin results from the inspiration and reference to the 500 years tradition of organizing herring fairs through this Hanseatic city. The first herring market (Danish: herincks marke) was created in the medieval buildings of the New Market (Latin: forum novum) in 1495. The development of this type of trade was possible thanks to the ancient trade route that crossed Szczecin and the Baltic Sea. The wind tower design is located in the place of the former, but no longer existing herring market at the Grodzka and Staromiejska street, which is now an empty square near the still existing Cathedral Basilica of St. James.

![Figure 10. Karol G. Kowalski, Initial design of Herring Air Purifier Tower, Szczecin Port, 2017](image)

Designed by author the Herring Air Purifier Tower for Szczecin Port is also a good example of technology and environment coming in together and creating something mutually beneficial (figure10). Under the technological surface an active gypsum layer is hidden with the addition of TiO$_2$-N. The gravitational circulation of the air is provided by airspaces and perforations. The inner space is a place where the photocatalytic process is observable in which under the influence of UV radiation occurs the mineralization of environmental pollutants.

6. Conclusions

In last decades’ impact of various environmental conditions, such as global warming and needs to reduce CO$_2$ emissions play an increasingly decisive role in the design of new architectural and civil engineering structures. Understanding the interrelation between these impacts and the built
environment put forth to architects and engineers to develop innovative materials, components and systems, in order to design active building envelopes. Nevertheless, air pollution with exhaust gases is one of the greatest current environmental problems. In large urban agglomerations, intense traffic increases the concentration of air pollutants. It especially concerns the nitric oxide NOx content. Air purification in cities is one of the crucial challenges of the 21st century. The development of visible light active photocatalyst for the mineralization of environmental pollutants has attracted considerable attention during last years. However, these achievements require popularization and social acceptance.

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