Cooler catalytic converters: Cleaner air for all

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Credit: AI-generated image (disclaimer)

As the lives of millions of people worldwide were disrupted by social distancing measures to combat the COVID-19 pandemic in early 2020, an unexpected piece of good news surfaced: levels of air pollution in major cities had dropped by up to 50% due to the global reduction in traveling, manufacturing, and construction. The most dramatic effects were seen in India, home to 14 of the 20 most polluted cities on Earth, where people posted photos on social media showing blue skies and clear air for the first time in recent memory.

The temporary reprieve was a stark reminder that the engine of modern society runs on the combustion of fossil fuels, which releases a noxious mix of chemicals into the air including poisonous carbon monoxide gas, VOCs (volatile organic compounds) like formaldehyde that can cause cancer, and nitrogen oxides that react with VOCs to create ozone, which causes breathing problems and even premature death. The World Health Organization estimates that seven million people are killed every year due to air pollution, and Greenpeace Southeast Asia has reported that polluted air costs the world trillions of dollars in medical care annually.

The problem of dirty air is not a new one: even burning wood releases toxic chemicals that can cause health issues when inhaled. But the explosion of manufacturing during the Industrial Revolution led to unprecedented levels of air pollution that continued largely unchecked through the early 20th century, exacerbated by the widespread adoption of gasoline-burning cars. There were no effective ways to remove pollutants from exhaust fumes until the 1950s, when mechanical engineer Eugene Houdry invented the first catalytic converter to address the black smog that was choking Los Angeles and other American cities.

Catalytic converters make use of a catalyst, usually an expensive metal like platinum or palladium, to speed up the chemical reactions between oxygen and pollutants in the air to convert them into less toxic byproducts like water vapor, carbon dioxide, and nitrogen gas. Directing exhaust fumes through a metal housing coated with the catalyst can remove up to 98% of pollutants from them, and regulations requiring the installation of catalytic converters on cars and smokestacks have helped dramatically improve air quality in cities around the world since the 1970s.

Despite the success of catalytic converters at reducing the pollution released by each car or factory, the dramatic increase in the number of vehicles and industrial buildings on the planet over the last 50 years has caused an overall decline in air quality. Research into atmospheric chemistry has revealed that the composition of exhaust is more complex than originally thought, and multiple stages have had to be added to catalytic converters to remove different pollutants, increasing their cost. Also making them more expensive is the scarcity of the precious metals used to catalyze the reactions—today, platinum costs about $785 per ounce. Not only does that expense limit the installation of catalytic converters to large manufacturers with deep pockets, it drives a thriving crime business in which thieves steal the catalytic converters from cars and sell them on the black market for the metals they contain. Replacing a catalytic converter can easily cost over $1,000, which many people in lower-income countries simply can't afford, so they continue to drive vehicles belching unfiltered pollution.

Tiny structures, big impact

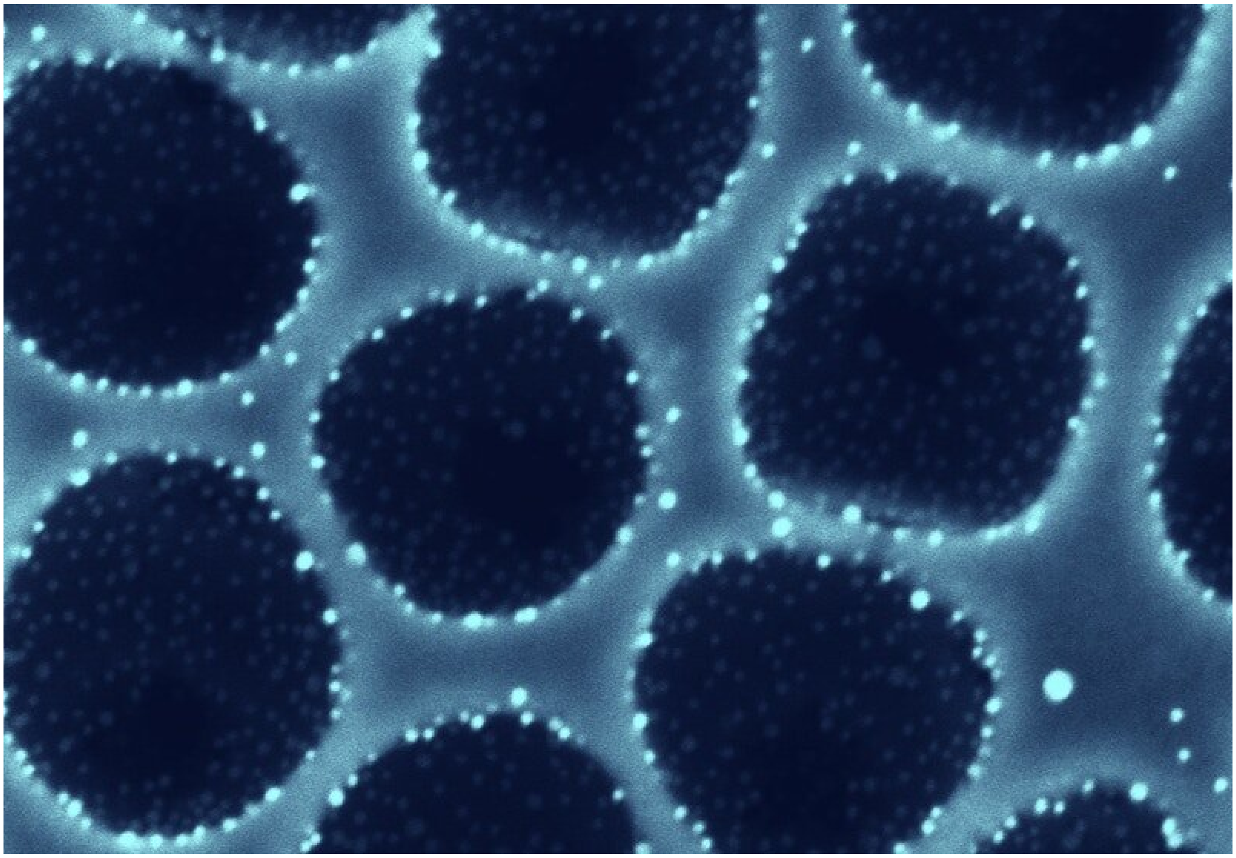
Any solution to this multifaceted problem has to strike a tricky balance of reducing the cost of catalytic converters without compromising their performance, and needs to be flexible enough to remove multiple different substances from exhaust. While working in the lab of Wyss Core Faculty member Joanna Aizenberg, former Wyss Institute researchers Tanya Shirman, Ph.D. and Elijah Shirman, Ph.D. discovered that Nature created just such a solution millions of years ago that has been hiding in plain sight ever since: butterfly wings.

When inspected under a microscope, the surface of a butterfly's wing is revealed to have a porous, rigid architecture that gives the wing its unique physical properties, including color, water resistance, stability, and temperature control. The Shirmans realized that they could mimic this nanoscale architecture to create a customizable scaffold for catalysts that would allow them to control everything from the composition, size, and placement of the catalytic nanoparticles to the shape and pattern of the scaffold.

"Catalytic converters today have three major problems: they are expensive because of the precious metals, they are inefficient because a lot of the catalyst never comes in contact with the air it's supposed to clean, and the catalysts only work within a specific temperature range, so before a car or a factory 'warms up," they're just spewing pollution that isn't cleaned," said Tanya Shirman, who now VP of Material Design at Metalmark. "Right now, you would need to develop separate materials to address the problems of cost, performance, and temperature stability, but our technology can solve all three issues at once."

The team has created a prototype in which nanoparticles of the catalyst are placed at precise points on the honeycomb-like organic colloid scaffold to ensure that all of the catalyst gets exposed to exhaust, minimizing waste and producing more efficient cleaning. It can also operate effectively at lower temperatures than a typical catalytic converter, reducing both the pollution released by "cold" engines and energy consumption. Importantly, the system is designed to integrate seamlessly into the existing catalytic converter production process. Because 70-90% of the manufacturing cost comes from purchasing the catalyst metal, a simple switch to the Shirmans' design could enable the production of much cheaper catalytic converters, making air purification more affordable and hopefully causing fewer thefts.

From the lab bench to the power plant



The butterfly-wing-inspired architecture allows precious metal catalysts (white) to be strategically placed on the porous scaffold (gray) so that the catalytic reaction is much more efficient and cost-effective. Credit: Wyss Institute at Harvard University

The Shirmans first started testing their idea in the lab in 2016, and were able to show that their system produced a very active and stable catalyst. But their sample was only about 50 milligrams in size (about 1/100th of a teaspoon), and they knew they would have to test it at a larger scale to prove that it could work on real catalytic converters. They submitted their project to the Harvard President's Innovation Challenge in 2017 and won second place, which gave them confidence that it had the potential to succeed commercially as well as technically. That same year, they applied and were accepted as a Validation Project at the Wyss Institute, and spent the next two years working on optimizing and scaling up their technology.

Last month the team has since taken another giant leap toward their goal of making cleaner air a reality by creating a startup company, Metalmark. Their most recent prototype was recently validated by a specialized National Lab and is now being tested by an industrial partner.

"Most of the new materials developed in academic labs never make it to market because they work really well on a small scale, but mass-manufacturing them while still preserving their function is very difficult and expensive. We started this project from scratch, from an idea, and in just a few years it's almost at the point where it can work in a giant power plant to purify large amounts of air," said Elijah Shirman, who is now VP of Technology at Metalmark.

In addition to large power plants and cars, the team has their sights set on applying their technology to indoor air purification for homes, offices, and other buildings. Indoor air offers its own unique set of challenges: the types and amounts of pollutants vary dramatically from building to building, and it would take a large amount of energy to heat the air to a temperature where the current catalysts can work, then cool it back down to a comfortable level. But the Shirmans believe that with a few more engineering tweaks, their technology could get there.

"This platform is extremely flexible, and allows us to quickly address specific problems that might come up regarding air purification. For example, it could be equipped with antiviral properties to filter virus particles out of the air, which would help reduce infections in hospital settings and could be deployed during future pandemics to help save lives," said Tanya Shirman.

Provided by Harvard University