Department of Bioresource Engineering

BREE 495: Engineering Design III

Zeolite Exhaust Emissions Filter

Group 4

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ABSTRACT

Fortunately, most modern cars are equipped with catalytic converters or diesel particulate filters. These devices are incorporated in the exhaust systems of motor vehicles and contain catalysts that convert harmful pollutant gases into less harmful ones. Although the gases that come out of catalytic converters and diesel particulate filters - partially combusted hydrocarbons such as soot and black carbon, carbon dioxide (CO_2) and volatile organic compounds (VOC) - are less harmful than those that enter, they can still have negative effects on air quality, the environment and human respiratory health. This paper conceptualizes a small, user-friendly detachable device that uses zeolites to capture these harmful pollutants that are not taken care of by the catalytic converter. This device is intended for individuals who care about their impact on the environment and have no other choice but to use motor vehicles. The design of such a filter, including all considerations and limitations, is discussed in detail.

1. INTRODUCTION

As mentioned, modern cars with gasoline and diesel internal combustion engines are equipped with catalytic converters and diesel particulate filters (DPF), respectively. Catalytic converters transform hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NOx) from the engine into less harmful CO_2, N_2 and H_2O through chemical reactions catalyzed by Platinum, Rhodium and Palladium. More on DPFs in the following section. The goal of this project was therefore to design a filter to capture harmful substances from exhaust gas. This design was initially intended specifically for gasoline engines, but once zeolites were chosen as the filtration material, the scope was broadened to both diesel and gasoline engines due to the excellent and varied filtration properties of zeolites.

Many particulate filters were considered for the purpose of this design, including gravity settling chambers, scrubbers, bag or fabric filters, cyclone filters, electrostatic precipitators, rotating fluidized bed filters, diesel particulate filters and biological physical filters. Extensive research was conducted on each type of filter. Using a Pugh chart to compare the properties of each filter with important design criteria, it was determined that a design based on a DPF would be most efficient at extracting pollutants from exhaust gas. Considerations and constraints for this design included:

1. *Safety*: All materials used needed to be heat resistant up to the temperature of exhaust gas, which is approximately 500°C. Furthermore, the filter could not cause significant back pressure in order to prevent engine suffocation. The device also needed to be safe for the user to handle.
2. *Effectiveness*: A filtration material that effectively trapped the targeted pollutants while simultaneously meeting the other design criteria was necessary.

3. *Sustainability*: In order to consider sustainability throughout the entire lifecycle of the design, the idea was to use durable, reusable material for the filter casing and sustainably sourced and safely disposable material for the filter itself.
4. *Economy*: The device needed to be inexpensive to manufacture in order for the final product to be economically worth it for the consumer.
5. *Practicality*: A lot of importance was placed on making the device user-friendly. It is for this reason that the device was designed to be easily detachable and adaptable to many sizes of exhaust pipe.

The aspects of the DPF exploited by this project were the honeycomb structure, to prevent back pressure and pressure loss, and the use of a porous, catalytic material to trap or chemically transform pollutants. Another aspect of the DPF that this device hoped to emulate was the very high efficiency. The following step, which proved to be the most challenging, was therefore to choose an appropriate filtration material. DPFs use materials such as porous silicon carbide ceramics. However, based on the suggestions of our mentors and for the sake of exploring a novel technology, zeolite membranes were ultimately chosen for their adsorption abilities. That said, an innovative prototype was built combining aspects of three existing technologies: zeolite membranes, the CO2ube, and DPFs. The next section is a study of all three of these technologies. The prototype was then tested and optimized, and a life cycle and cost analysis were performed. Even so, the fact that zeolite-enriched air filters were used instead of an actual zeolite membrane, since the zeolite membrane was too difficult to obtain, made testing and analysis difficult.

The zeolite exhaust emissions filter was designed with a general client in mind: individuals like us, who are concerned about the impact of traffic pollution on air quality but must use motor vehicles out of necessity for long daily commutes. Therefore, we approached a local mechanic shop, Carstar St-Leonard Le Creusot, and offered to design this device for their environmentally conscious clients. They set criteria and offered suggestions throughout the design process.

2. LITERATURE REVIEW

Zeolite Membranes

Natural zeolite is a rock composed of aluminum, silicon and oxygen. Zeolites have a natural porosity because of their crystalline structure which give them the ability to trap particles in their pores, called cages (CATC, 1998). They occur naturally near volcanic earth deposits and are produced as the result of the interaction between ash, volcanic rock and underground water. The types of natural zeolites that offer the greatest promise for gas separation applications include clinoptiolite, chabazite, mordenite, erionite, ferrierite and phillipsite (Ackley, et al., 2003). Clinoptilolite and chabazite are judged the most versatile, while also offering unique adsorption characteristics (Ackley, et al., 2003). Natural zeolites are often available in a powdered form. Zeolites are composed of a network of SiO_4 and M^2O_4. M^2 is trivalent and forms an oxidic skeleton with Si (Deeba, 2005). The individual tetrahedrons are attached to one another by oxygen bridges via the corners of the tetrahedrons to form a 3D network uniformly permeated by passages and voids (Deeba, 2005). Figure 1 below demonstrates what a zeolite crystal looks like.

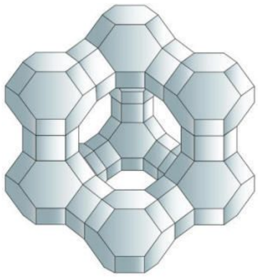


Figure 1: Crystal structure of zeolites.

Although zeolites are most commonly thought of as the powdered material mentioned above, they can in fact be synthetically grown as films on a variety of supports, both inorganic (e.g. glass, ceramic, metal) and organic (e.g. plastics, cellulose, wood) (Kulprathipanja & Santi 2010). This allows the transfer of some of the characteristic properties of zeolites powders - adsorption, catalysis, molecular recognition and diffusion - to a 2-dimensional structure, with potential applications in areas ranging from reactor engineering to molecular separations and chemical analysis (Kulprathipanja & Santi 2010). Therefore, the characteristics of zeolite films can be manipulated depending on the intended application, and the preparation procedures must be tailored accordingly (Kulprathipanja & Santi 2010). Although natural zeolites are abundant and inexpensive, these attributes may not offset the effects of impurities and inconsistency of properties relative to the more uniform synthetic zeolites (Ackley, et al., 2003). There are two main methods used for zeolite membrane synthesis (Ye, 2016):

1. *In-situ synthesis*: A support is placed in a synthesis solution, where crystals nucleate and grow into a film.
2. *Secondary growth*: Zeolite seeds are prepared, deposited on supports and film is grown by hydrothermal treatment. This approach prevails due to high reproducibility and good control over membrane thickness and orientation.

Important properties that can be manipulated by zeolite synthesis, other than thickness and crystal orientation, include prevention of defects and Si/Al ratio - which affects polarity and adsorption properties. Membrane selectivity is affected by adsorption properties. This ratio can be manipulated during the synthesis of the membrane to favor adsorption. The International Zeolite Association uses three capital letters to represent different zeolite frameworks, such as MFI, LTA and FAU (Ye, 2016). MFI zeolites with Si/Al ratios ranging from 10 to infinity have two sub-groups, namely ZSM-5, with a Si/Al ratio of 10–200, and silicalite-1, with a Si/Al ratio of more than 200 (Ye, 2016). Membrane selectivity can also be enhanced by introducing foreign chemical groups. MFI membranes appear very often in gas separation, molecular sieving and adsorption applications. The average pore diameter of MFI structures 0.55 nm, which means they have the possibility to separate small gas molecules based on adsorption selectivity in addition to molecular sieving (Ye, 2016). Many papers have shown that MFI membranes have the ability to sieve CO_2, VOCs and soot, which is why it is suitable for this design.

The adsorption ability of zeolite membranes provides an advantage over costly, energy-intensive alternative separation methods such as distillation, absorption and thermally-driven separation processes (Ackley, et al., 2003). In fact, membrane separation processes consume 6 to 10 times less energy than thermally driven processes (Ye, 2016). They also possess superior qualities to polymeric separation methods currently used, including higher flux and selectivity and higher chemical and thermal stability (Ye, 2016). In fact, zeolite membranes can operate at a very wide range of temperatures, from cryogenic temperatures (62-110K) to temperatures as high as those of the exhaust gas discussed in this project (700K). It is also for this reason that they have great potential for a variety of gas and liquid separations driven by pressure, concentration and temperature gradients (Ye, 2016). Thin membranes are most desirable due to high transport rates and permeability. They are also attractive due to low capital costs, simple and continuous separation, small space requirement and easy scalability (Ye, 2016).

The support is often the most costly part of the membrane, so they are often reduced to be more cost-competitive for industrial applications. The Ye research group has developed membranes comprised of thin (<1μm) zeolite films on aluminum supports with high flux and selectivity, that have been tested in both liquid and gas applications (Ye, 2016). These membranes would be a good candidate for this design.

CO2ube: Carbon Dioxide Filtration System

In 2013 an invention by 19-year-olds Param Jaggi and Jonny Cohen called the CO2ube was released into the world (Lynch 2013). The device aimed to reduce carbon dioxide emissions through the use of an attachable vehicle exhaust filter. The CO2ube seizes carbon dioxide released from a car's exhaust, allowing it to leach away, or converts it into less harmful byproducts using two chemical reactions (Lynch 2013). Figure 2 below is what the CO2ube looks like.

Figure 2: CO2ube filter developed by Param Jaggi

The first reaction the exhaust gas undergoes is through photosynthesis, a plant's reaction for conversion of sunlight into food and oxygen (Lynch 2013). Photosynthesis requires two molecular reactants, water and carbon dioxide, which are also byproducts of combustion (Lynch 2013). In the CO2ube, an algae-based filter filters gases that pass through while absorbing the carbon dioxide, resulting in the release of oxygen, glucose and smaller amounts of carbon dioxide (Lynch 2013). Figure 3 below is a technical diagram of the CO2ube.

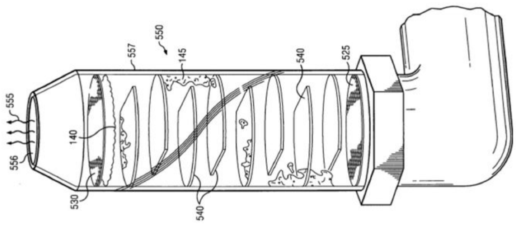


Figure 3: Internal view of the CO2ube

Because algae synthesis is not sufficient enough to rapidly reduce all of the carbon dioxide, a second reaction takes place ("CO2ube : The World's First Carbon Dioxide Filtration System."). Plates are fitted in the device to expand the surface area of the exhaust steam and act like a coolant, turning much of the carbon dioxide gas into its aqueous form ("CO2ube : The World's First Carbon Dioxide Filtration System."). The following chemical reaction takes place:

$$\underset{\text{Carbon Dioxide}}{CO_{2\,(aq)}} + \underset{\text{Water}}{H_2O_{\,(l)}} \rightarrow \underset{\text{Carbonic Acid}}{H_2CO_{3\,(aq)}}$$

$$\underset{\text{Carbonic Acid}}{H_2CO_{3\,(aq)}} + \underset{\text{Sodium Hydroxide}}{2NaOH_{\,(aq)}} \rightarrow \underset{\text{Sodium Carbonate}}{Na_2CO_{3\,(aq)}} + \underset{\text{Water}}{2H_2O_{\,(l)}}$$

The carbonic acid that flows through the stream reacts with embedded sodium hydroxide, a very strong base, to produce sodium carbonate, a neutral and harmless product to the environment ("CO2ube : The World's First Carbon Dioxide Filtration System.").

This device can be incorporated into any exhaust pipe and retails for approximately $60USD (Lynch 2013). The founding company, Ecoviate, has also released partnering smartphone applications that allow tracking of vehicles carbon emissions (Lynch 2013).

<u>Diesel Particle Filter</u>

Diesel Particulate Filters (DPFs), are devices used to capture diesel particulates emitted from diesel-driven internal combustion engines. This method of filtration has become one of the most effective ways to control diesel emissions as it has demonstrated high filtration efficiencies of over 90%, as well as suitable mechanical and thermal durability (Majewski, 2001). In addition to carbon monoxide and hydrocarbons, diesel engines emit nitrogen oxides and particulate matter such as soot. DPFs are most effective in trapping solid fractions of diesel particulates, such as black carbon, contrarily to the non-solid fractions of particulate matter emissions, like sulfate particulates.

Although there are many configurations are available, the wall-flow type is the one that is most commonly used Diesel Particulate Filter (Rodríguez-Fernández et al., 2016). This configuration is an extruded and most often cylindrical structure embedded with parallel-axial flowing channels. While this honeycomb design might be derived from catalytic converters used in modern-day vehicles, there are some important differences that need to be considered (Majewski, 2001). For one, their wall-flow monolith structures are made with more durable ceramics with controlled porosity. Secondly, the adjacent channels embedded in DPFs are alternatively closed-off at each end, preventing black carbon particulates from reaching the atmosphere, while allowing filtered air to be passed through the exhaust. Figure 4 below shows the honeycomb structure of DPFs.

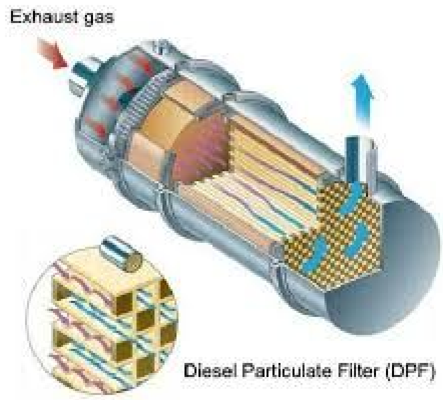


Figure 4: Honeycomb structure of a diesel particulate filter

It is important to note that Diesel Particulate Filters can accumulate large amount of soot within their wall-flows due to the low bulk density characteristics of diesel particulates (< 0.1 g/cm3) (Majewski, 2001). This black carbon accumulation can be very problematic if not properly eliminated. By blocking the flow gas combustion gases, an excessive gas pressure drop can be caused by the filter, which can greatly reduce engine functionality. Therefore, effective measures must be made in order to ensure proper soot removal and restore the filter's soot collection capacity in DPFs. One of the most commonly used methods for black carbon removal consists of filter regeneration (Majewski, 2001). Filter regeneration can be done in two different ways: continuously or periodically. Continuous regeneration is performed while the vehicle is being driven and the filter is operating, while periodical regeneration is performed once a certain amount of soot has accumulated in the filter. Sometimes, thermal regeneration is performed, removing the excess black carbon through oxidation processes with the use of carbon dioxide (Majewski, 2001).

3. DESIGN DESCRIPTION

Assumptions and Safety Considerations

When designing an exhaust filter that will be incorporated into an exhaust system, there are some parameters that need to be determined prior to prototype building to ensure that the filter does not affect the overall performance of the vehicle and does not put clients at risk. As an approximation, the properties of air will be used to simulate the conditions inside an exhaust pipe. Furthermore, for the purpose of our design, the parameter calculations will be done under the assumption that the exhaust pipe is straight and cylindrical. The back pressure in the exhaust pipe with and without the filter needs to be determined to make sure that the filter does not increase back pressure and block the exhaust pipe. The John Deere HPX 4x4 Gator XUV will be used for testing purposes, under the supervision of Scott Manktelow, thus it's specifications were used for the following calculations. The John Deere Gator has a diesel engine and 4 cylinders which were all considered during the design calculations. One key point worth emphasizing is that the determined values are theoretical and serve only to verify that the filter did not affect the back pressure. The temperature of the exhaust gas was assumed to be approximately 700 K (~700 °F). Since zeolites are known for having a high temperature threshold and for being able to perform within a large temperature range, it was a suitable material for our particular design. The following calculations are based off of the zeolite enriched air filter, used in the prototype, and are not representative of the ideal zeolite membrane meant to be used for the final design.

Calculations

To begin, the back pressure in the exhaust without the filter was established using the following equation, where P represents back pressure (kPa), L is exhaust pipe length (m), S is density (kg/m^3), Q is exhaust gas flow (m^3/s), D is pipe diameter (m) and P_s is pressure drop in the silencer (Pa) (Eng-tips, 2017).

$$P = \frac{L\ x\ S\ x\ Q^2\ x\ (3.6\ x\ 10^6)}{D^5} + P_s$$

S = 0.5075 kg/m^3

L = 1m

D = 2 inches x $\frac{25.4\ mm}{1\ inch}$ = 50.8 mm = 0.0508 m

The density of the exhaust gas was interpolated using the values of air as previously mentioned, at a temperature of approximately 700 K (Jaaskelainen, 2011). The temperature of the exhaust gas, 700 K is also an approximate value based on whether or not the vehicle was equipped with a DPF (Gonzales, 2008). The length and diameter of the exhaust pipe were estimates as well. The exhaust gas flow (Q) was found using the following equation (Donaldson).

$$Exhaust\ flow\ (cfm) = \frac{Exhaust\ Temperature\ (°F)\ + 460}{540}\ \text{x}\ Intake\ Airflow\ (cfm)$$

However, in order to determine the exhaust flow, the intake airflow needed to be calculated first using the formula below for 4-cylinder engines (Donaldson).

$$\begin{aligned} Intake\ airflow\ (cfm) &= \frac{Engine\ size\ (CID)\ x\ RPM}{3456}\ \text{x}\ Volumetric\ efficiency \\ &= \frac{52.1\ CID\ x\ 1000\ rpm}{3456}\ \text{x}\ 0.90 \\ &= 14\ \text{cfm} \end{aligned}$$

Engine size = 854 cc (diesel engine)

$$\begin{aligned} &= 854\ \text{cm}^3\ \text{x}\ \frac{0.06101\ inches^3 (CID)}{1\ cm^3} \\ &= 52.1\ \text{CID} \end{aligned}$$

The value for the engine size was taken directly from the HPX John Deere Gator specifications (John Deere, 2017). The engine speed was assumed to be around 1000 rpm as the engine was idle during testing. The volumetric efficiency was taken to be 0.90, as the Gator was a 4 cylinder diesel engine (Donaldson).

$$\begin{aligned} Exhaust\ flow\ (cfm) &= \frac{700°F\ + 460}{540}\ \text{x}\ 14\ \text{cfm} \\ &= 29\ \text{cfm} \end{aligned}$$

$$\begin{aligned} Q &= 29\ \text{ft}^3/\text{min x}\ \frac{0.0283168\ m^3/min}{1\ ft^{3/}min} \\ &= 0.82\ \text{m}^3/\text{min x}\ \frac{0.0166667\ m^3/s}{1\ m^3/min} \\ &= 0.014\ \text{m}^3/\text{s} \end{aligned}$$

The drop pressure in the silencer was assumed to be 2.5 kPa, which was the value obtained for a similar engine. In essence, the first part of the equation is the one that is most important and is the one that will vary based on whether the filter is included or not.

$$\begin{aligned} P &= \frac{L\ x\ S\ x\ Q^2\ x\ (3.6\ x\ 10^6)}{D^5} + P_s \\ &= \frac{1m\ x\ 0.5075\ kg/m^3\ x\ \ (0.014\ m^3/s)^2\ x\ \ (3.6\ x\ 10^6)}{(0.0508\ m)^5} + 2500\ \text{Pa} \\ &= 13\ \text{x}\ 10^3\ \text{Pa} = 13\ \text{kPa} \end{aligned}$$

Now, when considering the back pressure with the exhaust filter there are some parameters that need to be changed slightly; the length of the filter (L) and the diameter of the filter (D). The values for the length and diameter are general educated assumptions. The zeolite enriched air filters need to be considered when measuring the diameter of the filter. Each individual filter has a thickness of about 2 mm, therefore the width of the two zeolite enriched layers was subtracted from the total diameter. This thickness is representative of the filter used in the prototype, but is different from the actual thickness of zeolite membranes.

$$D = 1.75 \text{ inches x } \frac{0.0254\ m}{1\ inch} = 0.044 \text{ m} - (2 \text{ x } 0.002 \text{ m}) = 0.040 \text{ m}$$
$$L = 0.33 \text{ m}$$

$$P = \frac{0.33m \ x \ 0.5075\ kg/m^3 \ x\ (0.014\ m^3/s)^2 \ \ x\ \ (3.6\ x\ 10^6)}{(0.040\ m)^5} + 2500 \text{ Pa}$$
$$= 14 \text{ x } 10^3 \text{ Pa} = 14 \text{ kPa}$$

The difference in back pressure with and without the filter varies only slightly indicating that the filter does not cause a significant increase in back pressure.

Design Implementations

In order to construct a feasible prototype of our zeolite exhaust emissions filter, it is necessary to consider certain required materials:

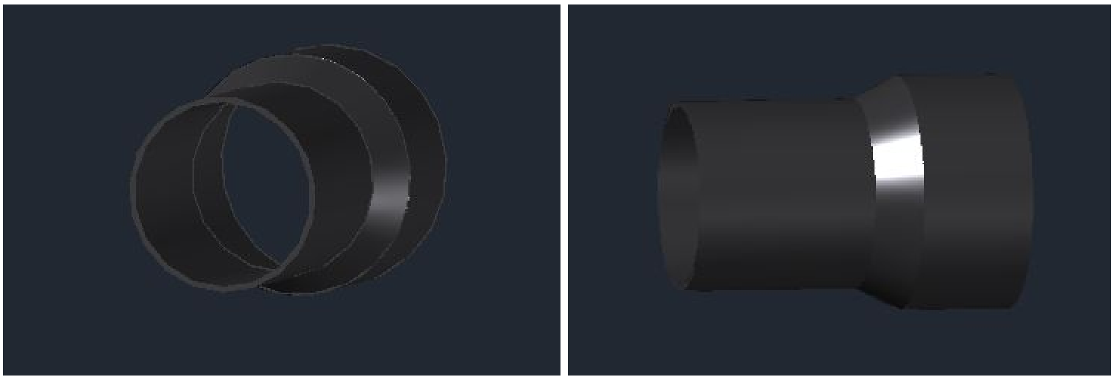
- 1¾" 409 Stainless Steel Cylindrical Tailpipe Casing
- Zeolite enriched air filters
- Metal wires
- Clamp
- Adapter
- Attachment bracket

The implementation of each component of our exhaust emissions filter will be thoroughly discussed in the following literature.

Automobiles exhaust tailpipes come in various shapes and configurations. Upon analysis of currently used vehicular tailpipes in stock automobiles, we have observed that the most commonly implemented tailpipes consist of stainless steel cylinders with varying diameters. Once having determined the shape of the tailpipe, it is important to consider the varying sizes attributed to these exhausts. This process was done by purchasing multiple cylindrical exhaust tailpipes (1 ¼", 1 ½", 1 ¾", 2" and 2 ½") from Canadian Tire® and testing them on several different types of cars (Mazda 3, Nissan Versa, Lexus RX330, Dodge Ram 1500 and John Deere 4x4 Gator). This trial and error process allowed us to eliminate the 1 ¼" and 1 ½" exhaust pipes since they were too small for each tested vehicle. On the other hand, the 2" and 2 ½" exhaust pipes were too big for the smaller compact cars (Mazda 3, Nissan Versa), however, they were compatible with bigger vehicles like the Lexus RX330 and the Dodge Ram 1500. Finally, we decided to use the 1 ¾" exhaust tailpipe since it was compatible with the smaller compact vehicles and could be modified to fit larger tailpipes with the help of an adapter (more on this later). Therefore, this simple experimentation allowed us to determine an exhaust tailpipe that will serve as a norm for every vehicle while still being able to be adaptable to any automobile with a cylindrical exhaust tailpipe.

The material used to make our 1 ¾" cylindrical exhaust emissions filter casing consists of 409 Stainless Steel. This ferritic type of steel has high temperature corrosion resistance as well as high mechanical strength, essential for enduring exhaust gas temperatures (A.K, 2007). This is very important because the outer casing of our prototype - which is embedded in vehicular exhaust tailpipes - is used to hold the zeolite membrane filter, therefore, it is necessary for it to be durable and long lasting.

To increase the compatibility of our prototype, we have decided to include attachable adapters to our prototype casing. This allows us to market our zeolite exhaust emissions filter to a wider range of clientele without having the modify the prototype itself. The adapters, shown in figures 5 and 6, are made from the same 409 Stainless Steel as the cylindrical exhaust casing and come in virtually any size. This simple adaptation increases the feasibility of our design since it can be readily detached from vehicular tailpipes when needed. The method of attachment is as follows: The small end of the adapter attaches onto the casing of the prototype, while the end with the bigger diameter is fixed inside the tailpipe. This ensures that all the exhaust gases pass through the zeolite filter prior to exiting the tailpipe, therefore maximizing filtration efficiencies.



Figures 5 and 6: Computer aided designs of the adapter

As previously stated, our preferred filtration material consists of synthetically manufactured zeolite membranes. However, since these filters are very inaccessible, we constructed our prototype from zeolite enriched air filters. Although this filtration material cannot be compared to efficiencies seen in zeolite membranes, it still provides us with an idea of how such a filter would function and proof that it can be considered as a potentially favorable solution to this environmental issue.

Due to high filtration efficiencies and simple design, we have decided to create our zeolite exhaust emissions filter using the method of filtration implemented in diesel particulate filters. Our design consists of a cylindrical monolith wall-flow filter, which is placed at the tip vehicular exhausts. Monolith wall-flow filters, also referred to as honeycomb filters, serve to effectively trap in soot and other volatile organic compounds, while providing an efficient pathway for filtered air to flow out the exhaust tailpipe (Rodríguez-Fernández et al., 2016). This method of filtration has become one of the most effective ways to control exhaust emissions as it has demonstrated high filtration efficiencies of over 90%, as well as suitable mechanical and thermal durability (Majewski, 2001). Thus, this allows us to create a filtration method that provides a balance between soot and VOC filtration, while limiting engine back pressuring. Figure 7 below is a computer aided design of our prototype, showing the monolith wall-flow structure of our zeolite exhaust emissions filter.

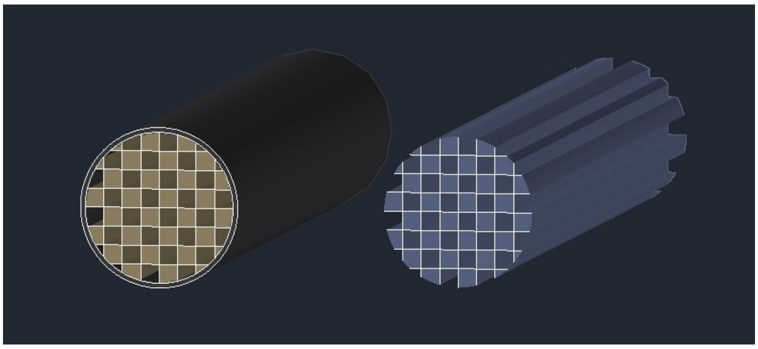


Figure 7: Computer aided design of the monolith wall-flow filtration system

Furthermore, in order to ensure that the zeolite filter remains embedded within the cylindrical casing of the exhaust tailpipe, a secured capping mechanism is required. Using thin yet durable metal wires, we created a mesh-like cap to be secured to the tip of the exhaust emissions prototype (figure 8). A metal clamp was used to tightly fasten the cap onto the cylindrical casing of our prototype and can be detached or adjusted using a flat-head screwdriver. This open-style design allows for gasses to easily flow through the exhaust whilst minimizing potential back pressuring that can be created with the use of other closed caps. In addition, this also allows the user to easily remove the cap when in need of replacing the zeolite filter and attach it back accordingly. The final addition to our prototype is an attachment bracket which is used to secure the zeolite exhaust emissions filter to the tailpipe of automobiles. This attachment bracket is affixed on the exhaust and bound tightly using the same metal clamp.

Figure 8: Image of our Exhaust Emissions Filter embedded in the tailpipe of a Mazda 3

An important aspect to consider is the regeneration of our Zeolite Exhaust Emissions Filter. Conventional Diesel Particulate Filters are usually placed right after catalytic converters or turbochargers due to high gas temperatures which are essential for continuous and periodical regenerations (Majewski, 2001). However, since our filter is located at the exhaust tailpipe, conventional regeneration processes - involving high temperature gas to remove the soot out of diesel particulate filters - will not be a feasible regeneration method. Therefore, our zeolite membrane filter will be carefully disposed and recycled at *DPF Recovery Inc.* located in Somerville, Alabama. *DPF Recovery Inc.* is a well known company that deals with the recovery of soot and ash accumulation in diesel particulate filters. Once used to its full capacity, our zeolite membrane filters will be shipped to *DPF Recovery Inc.* and undergo their proper recyclation procedures.

Optimization, the final step of the design process, involves making modifications to the original filter prototype based on the results obtained during testing. This is done to ensure that any problems encountered during testing are solved immediately, essentially improving the initial design. Fortunately, there weren't many changes or improvements made to our filter as it performed quite well under the circumstances. However, one issue observed during the first testing period was that the zeolite enriched air filter flew out of the metal casing as a result of the exhaust gas. Therefore, in order to prevent this from reoccurring, a metal wire mesh was fastened at the end of the exhaust filter to keep the zeolite filter secure and in place. Another modification made during the design process was the switch from a metal honeycomb structure reinforced with zeolite infused filters to a honeycomb structure made purely from zeolites to allow for more flow in the filter. Finally, there were many modifications made to attach the filter to the exhaust pipe.

4. TESTING METHODS

Testing Protocol

After completing the fabrication of our prototype, we performed several tests on a John Deere HPX 4x4 Gator™ XUV provided at the Macdonald Machinery Shop with the supervision of Scott Manktelow. The testing protocol is as follows:

1. Place the prototype zeolite exhaust emissions filter inside the tailpipe of the John Deere HPX 4x4 Gator™ XUV
2. Fasten the prototype onto the tailpipe tightly, as to prevent the filter from exiting the exhaust
3. Once secured, turn on the John Deere HPX 4x4 Gator™ XUV and wait until the glow-light has been turned-off
4. Start the ignition and run the motor for 2 minutes*
5. After the test run has been completed, safely remove the exhaust filter prototype out of the vehicle's tailpipe using heat-sensitive gloves
6. Repeat steps **1-6** for 4, 6, 8, and 10 minute tests
7. Remove the filter out of the prototype for further analyzation by SEM

The filter was tested for periods of 2,4,6,8 and 10 minutes to determine how well it was maintaining as time went on. After each testing period, the filter was removed and observed to see if it was accumulating soot over time. Since zeolite membranes were not actually used for the prototype, the purpose of this test was simply to check that a physical filter placed at the end of a tailpipe had the ability to capture soot without burning or getting clogged too quickly. Of course, had our desired filter been used, we could have tested the zeolites adsorption abilities according to certain standards to better judge the efficiency. This test was also done to see if our filter could withstand the vibrations of the tailpipe without causing too much mechanical interference.

5. RESULTS

Scanning Electron Microscope (SEM)

The Scanning Electron Microscope (SEM) is a scanning instrument that produces images using high-energy electrons to generate signals at the surface of a solid sample. This results from the electron interactions of the specimen and provides information, such as the external morphology, the chemical composition and the crystalline structure (Goldstein, Joseph et al.). Two-dimensional images are produced from samples as small as 1 cm to 5 microns in width and can be magnified from 20x to 30 000x with spatial resolutions of 50 to 100 nm (Goldstein, Joseph et al.).

With the help of Yvan Gariépy, a professional associate at McGill University, an SEM instrument was used to determine whether a zeolite membrane material would adsorb any particulate matter from exhaust gas emissions.

Two 3x3mm samples of zeolite membrane material representing before and after being inserted into the exhaust emissions filter were placed into the SEM for observation. The following photographs were obtained:

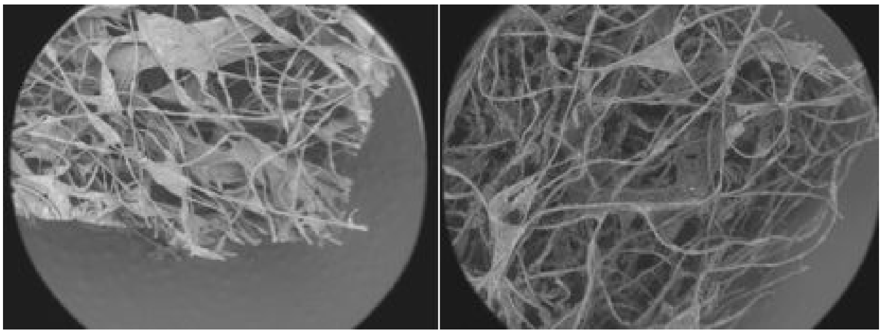


Figure 9: Right: *Zeolite membrane material before being inserted into exhaust emissions filter magnified at 30x*. Left: *Zeolite membrane material after being inserted into exhaust emissions filter magnified at 30x*

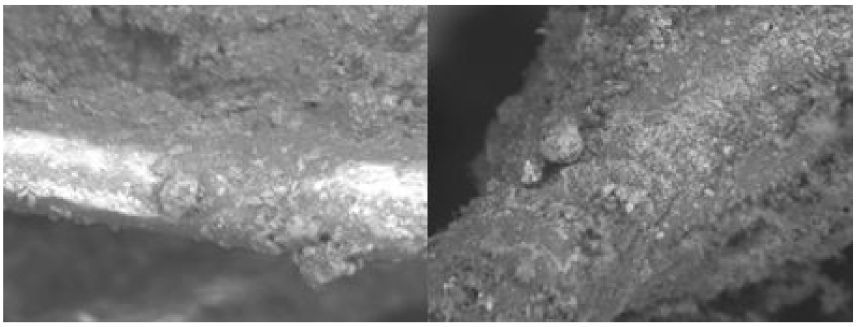


Figure 10: Right: *Zeolite membrane material before being inserted into exhaust emissions filter magnified at 1500x*. Left: *Zeolite membrane material after being inserted into exhaust emissions filter magnified at 1500x*

The above images obtained from the SEM instrument depict the successful adsorption of particulate matter by the zeolite membrane material. As a result, due to its favorable properties, it is a valuable textile to use as a collecting structure for soot.

6. ANALYSIS

<u>Production Analysis</u>

The goal of this design project is to reduce pollution and promote sustainability, therefore, sustainability must be considered throughout all stages of a product's life cycle. An important sustainable aspect of our design is that the metal casing, clamps and adapters are durable and reusable, and only the zeolite filter needs to be replaced when full.

Zeolites are used in various field applications, but in order to generally quantify the exhaust emissions filter's impact on the environment, a Life Cycle Assessment (LCA) should be performed. An LCA analyzes the environmental impacts of a product throughout its entire lifecycle, from creation, to use, to disposal.

There are many advantages to the use of zeolites, but it is also important to consider all of the material's environmental impacts and energy requirements. This would give a general idea about whether the overall use of a product is sustainable and about whether the positive outcome outweighs the negative impacts.

In the fabrication of this design, the use of synthetic zeolites was chosen instead of natural zeolites because, as previously mentioned, natural and synthetic zeolites share the same properties and have similar (if not better, engineered, more application-specific) structures.

Zeolites are commonly synthesized through hydrothermal or solvothermal methods conducted at high temperatures and high pressures, which consequently increases energy consumption during production (Yu. J, 2016). Added organic templates and organic solvents are frequently toxic and expensive. The products obtained after synthesis must further be calcinated at high temperatures to remove the obstructed organic templates, causing additional pollution (Yu. J, 2016). Although the synthesis of zeolite membranes is a very complex process that may be energy-intensive, membrane separation processes consume 6-10 times less energy than thermally driven processes (done for extracting natural zeolites) (Yu. J, 2016). Complex, energy-intensive, expensive, toxic zeolite synthesis methods may be considered a limitation for their use in industrial applications such as the application discussed in this project. However many chemists and engineers have put great effort into creating methods of zeolite synthesis that minimize ecological impacts and costs while maximizing energy efficiency and process safety. These methods of synthesis would include organic-template-free-synthesis, solvent-free synthesis, cheap or low-toxic organic-template-directed synthesis, waste reused synthesis, microwave-assisted synthesis, and ionothermal synthesis (Yu. J, 2016). Therefore, in order to assure that a detachable zeolite exhaust emissions filter would have a positive net output, minimal input can be considered by applying the greener processes of zeolite synthesis.

Another important factor to consider is the cost required to produce and maintain the product. The cost of filter replacement and the amount of time between each replacement should be carefully considered.

The following equation should be taken into consideration:

$$C_T = C_R A_C + C_I$$

Where $C_{T,}$ $C_{R,}$ and A_C represent the total manufacturing cost, replacement costs (per km driven) and distance driven (km), respectively.

The individual components used in the making of zeolite exhaust emissions filter and their purchase costs are as follows. These costs would be incorporated into the purchase price of the filter, since all of these components are reusable.

- 1 ¾" 409 Stainless Steel Exhaust Tailpipe = $10
- 409 Stainless Steel Exhaust Adapter = $7
- Metal Clamp = $1.50
- Metal Wiring = $2.50/$m^2$

The only price not included above is the price of the zeolite membrane filter. Due to the fact that the zeolite membrane filter was difficult to obtain, the complete cost analysis of our design was difficult to assess.

A study conducted in 2003 normalized the incremental cost of the minimal processing of clinoptilolite, a natural form of zeolite, in quantities greater than 10 000 kg with the cost of commercial zeolite 13X and obtained the following results (Ackley, et al., 2003):

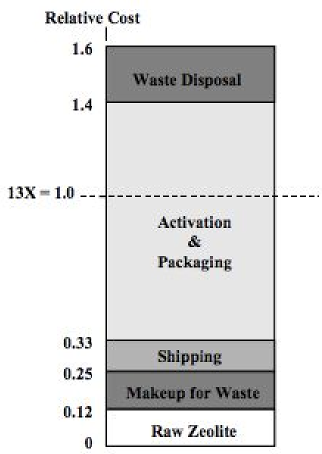


Fig. 1. Relative costs of processing a natural zeolite for use in gas separation.

The final cost of the natural zeolite adsorbent is 60% higher than 13X and more than 10 times higher than the original raw material cost. Therefore, they found that the low cost of the raw material used for more complex zeolite applications does not necessarily result in a lower adsorbent cost for a gas separation (Ackley, et al., 2003).

According to ACS Material, an advanced chemicals supplier, ZSM-5 catalysts, which are a type of MFI zeolite as mentioned above, are sold for $180USD per 200 grams ("ZSM-5 Catalyst Supplier- Molecular Sieves."). However, this is the price of the synthetic zeolite in the form of pellets, so the cost of the membrane formation itself is not taken into account. As many synthesis methods exist depending on the desired properties and applications of the membrane, it is very difficult to estimate the cost of the zeolite membrane intended for this design. However, as mentioned above, it is estimated that the final cost of natural zeolite adsorbent is 10 times greater than the raw material cost. Because an exact cost of the zeolite membrane material could not be accurately calculated, an overall cost for manufacturing and maintenance of the product could not be determined.

The most important part of the cost analysis would have been to determine whether this device was in the economic best interest of the user. However, this calculation was not possible since two key pieces of information were missing: the cost and the efficiency of the zeolite membrane. Testing our device with the actual zeolite membrane would have allowed us to determine how often the filter required replacing. With the replacement frequency and the purchase price of a new filter, the economic feasibility of the device could have been calculated.

7. RECOMMENDATIONS

<u>Gas Chromatography/Mass Spectrometry (GCMS)</u>

Many additional methods of testing could have been performed to obtain further data. A Gas Chromatography/Mass Spectrometry (GCMS) analysis could have been conducted to allow us to identify what exactly was captured by the filter as well as quantify how much was captured. However, due to time constraints and the inaccessibility of our preferred filter, it became difficult to undergo this testing method.

Gas chromatography involves volatilization, which is the process in which a dissolved sample is vaporized (Sparkman, O et al, 2011). The separation of the sample components is then done in a prepared column (Sparkman, O et al, 2011). This testing process could have provided us with additional data, thus improving our overall project.

<u>Recycling method of zeolite "soot-filled" membrane material filter</u>

The recycling of zeolite membrane material is taken into consideration in this project. As previously mentioned, *DPF Recovery Inc.* is a company that deals with the recovery of soot and ash accumulation in diesel particulate filters. Similarly, *Nespresso* is committed to protecting the environment and aims to promote sustainability through a recycling initiative in all of their boutique locations. The plastic capsules can be returned to the boutiques after they are consumed to ensure they are properly recycled (Coffee & Espresso Machines | Nespresso Canada 2016). There, the consumer can buy new coffee capsules to be used.

Based off of this proactive initiative, a similar idea can be applied to our exhaust filter. When buying a new zeolite filter, the package can include a special bag that is intended to be used to send dirty filters to *DPF Recovery Inc.* That way, it will ensure the proper recovery of soot to avoid ecosystem interruptions.

<u>Incentives</u>

This innovation requires multiple filter replacements after a predetermined period of time and thus does not benefit consumers in many ways, other than the satisfaction of knowing they're reducing their carbon footprint (Lynch, 2013). Therefore, certain incentives need to be put in place to attract more users.

CO2ube innovators have aimed to incorporate incentives to entice more consumers to use their design. Petitions have been initiated to allow CO2ube vehicles to ride in High-Occupancy Vehicle (HOV) lanes and Ecoviate has been working with the US Environmental protective agency to grant tax credits to CO2ube owners (Lynch 2013). The implementation of our exhaust filter on a large scale can be facilitated through the use of incentives with regards to transportation services. Drivers with our exhaust filter can have access to specified lanes, potentially reducing traffic volume.

8. CONCLUSION

This design was meant to be a step toward reducing air pollution. This project aimed to filter pollutants from vehicle exhaust that are not eliminated by catalytic converters or diesel particulate filters.

The zeolite emissions filter conceptualizes a combination of three technologies - diesel particulate filters, the CO2ube, and zeolite membranes - to create a single new innovation to capture harmful pollutants. The design of such a filter, including all considerations and limitations, is discussed in detail in this report. It was concluded that the most suitable design was a cylindrical metal casing, with an adapter for various sized exhausts, containing a zeolite membrane filter.

After testing a prototype made with a zeolite-enriched air filter rather than a zeolite membrane filter, and analyzing it with a scanning electron microscope, it was determined that the filter did indeed successfully collect particulate matter. If obtaining the actual zeolite membrane material were possible, more testing could have been done. This would have led to the determination of the maximum soot capacity, and ultimately the determination of the frequency at which the filter needed to be replaced. These would influence the overall cost of the product.

Safety, effectiveness, sustainability, economy, and practicality were all considered when building the prototype, as well as during optimization of our design. However, further optimization is required in order for this device to become implementable on a large scale.

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