

Using Organic Materials in Diesel Particulate Filters (DPF)

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Abstract: This study presents a discussion for fusing polymers as cells of the diesel particulate filter i.e., as a porous media. The transmission losses of sound waves and noise reduction will be calculated for different values of frequency and a comparison between ceramics and polymer filters is demonstrated. It is found that polymers cells improving transmission losses and noise reduction factor of the DPF.

Key words: Diesel particulate, noise reduction factor, organic materials, polymer, transmission losses

INTRODUCTION

All countries now are seeking from pollution especially that produced from heavy diesel vehicles, Jordan is one of these countries which has many problems in this field which can be represented by the weak specifications of diesel as a fuel- sulfur content (about 1.2% w/w)- (Mustafa *et al.*, 2010), and the very rapid increase in number of automobiles which cause more pollution, in addition to the shortage in energy sources which is a main reason in increasing prices of fuel in Jordan recently. Diesel particulate filters are considered as a good example of a porous media, also they are considered as one of the leading technologies to meet future Particulate Matter (PM) emission. These devices generally consist of a wall-flow type filter positioned in the exhaust stream of a diesel vehicle. As the exhaust gases pass through the system, particulate emissions are collected and stored. Because the volume of diesel particulates collected by the system will eventually fill up and even plug the filter, a method for controlling trapped particulate matter and regenerating the filter is needed. It is very important to discuss and understand the construction of DPF units, their properties, types, and their operation. It is worth to mention that all countries (including Jordan) attempt to use such devices in the close future. In order to complete understanding about the way to derive the acoustics governing equations for the DPF unit after it is connected on the exhaust system. There are many new technologies that are recently developed to reduce the exhaust gasses emission especially that produced from diesel engines includes (John *et al.*, 1997):

- Diesel Particulate Filters (DPF)
- Diesel Oxidation Catalysts (DOC)
- Crankcase emission controls
- Enhanced combustion modifications: e.g., cams, coating, superchargers, and engine rebuild kits.

Diesel Particulate Filter (DPF) is considered as one of the most efficient devices and the easiest to be installed and to be maintained. The diesel particulate filter is shown in Fig. 1.

Diesel Particulate Filter (DPF) is considered as a superior system which is used to reduction of particulate matters; where it can reduce about 69-85% particulate Matter (PM). (William, 2003) It contains a large numbers of thin tubes or cavities with a diameter of about (1-2 mm), and (0.15-0.5 m) length. There are many types of DPF's such as: electric heater type, burner type (ceramic filter), and fuel additive type; the latter type is a honey-comb ceramic. The honey-comb type constitutes an additive supply and an electronic system. In this type Iron (Fe) is used as an additive whereby iron oxide is formed which reacts with carbon and then it is converted to iron. When certain temperature is reached, the O₂ formed around iron oxide which reacts with the Particulate Matter (PM) so that these particles could be regenerated in the existence of O₂ from catalyst. (John *et al.*, 1981) For many diesel engines, the exhaust gas temperature is insufficient to regenerate the filter. To make the filter regeneration taking place effectively, exhaust temperatures require to exceed about 500°C for non-catalyzed systems, and 250 to 300°C for catalyzed systems. Some diesel particulate filters use a passive approach, and do not require an external or active control system to dispose of the accumulated soot. Passive filters are installed in place of the muffler. At idle or low power operations, particulate matter is collected on the filter surface. As the engine exhaust temperatures increase, the collected material is then burned or oxidized by the exhaust gas, thus cleaning or regenerating the filter. To ensure filter regeneration, various strategies are used. Regeneration methods include (Edward and Bissett, 2001):

- Coating the filter substrate with a base or precious metal, thereby reducing the temperature needed for oxidation of the diesel particulate matter.



Fig. 1: Diesel particulate filter

- Installing a catalyst upstream of the filter, and again lowering the exhaust temperature needed to burn off the particulate.
- Using fuel-borne catalysts to reduce the burn-off temperature of the collected particulates.
- Installing fuel burners, electrical heaters or some other active method to heat the exhaust gas to a high enough temperature to ensure PM oxidation. While limited to primarily off-road applications, another strategy which avoids filter regeneration altogether is to use a disposable particulate trap. The disposable system is sized to collect diesel particulate matter over a set period of operation. When full, the system is removed from the vehicle and replaced with a new unit. Diesel particulate filters are also very sensitive to exhaust gas temperatures and fuel sulfur content which effects on the performance of the DPF system. For most continuously regenerating catalyzed particulate filters to work properly, an engine must operate at around 300°C for 30% of the duty cycle or for 30 min. Some other types of diesel particulate filters require an average exhaust temperature of at least 27°C for 40% of the engine duty cycle. Exhaust gas temperatures are highly application dependent. Excessive heat loss in the exhaust system can cause lower exhaust gas temperatures, as can over-size engines that are operated low on their torque/power curve. Although many diesel applications generate sufficient exhaust gas temperatures for successful DPF operations, device manufacturers and regulators recommend that certain vehicle applications are equipped with data loggers to continuously monitor exhaust back pressure and temperature. Once it is determined that sufficient exhaust gas temperatures exist for filter regeneration, the monitoring can be stopped. Fuel sulfur content also affects the performance of passive DPFs. The Department of Energy (DOE) in USA recently concluded a study examining the effects of sulfur on diesel particulate filters. Two passive regeneration systems were tested: a catalyzed DPF (the filter is directly coated with a catalyst) and a continuously regenerating DPF (a catalyst is located upstream of the filter). DOE found that DPFs cease to reduce PM emissions with

fuels containing 150 ppm sulfur and become a source of PM emissions with 350 ppm sulfur fuels. (Jeffrey and Allison, 2005) Overall, baseline PM emissions increased as the fuel sulfur level increases. At 3 ppm sulfur both devices reduced PM emissions by 95%, and at 30 ppm sulfur the PM reduction efficiencies of both devices dropped to the around 72%. Diesel particulate filters can be installed on new and used automobiles, but must be used in conjunction with Ultra-Low Sulfur Diesel (ULSD) fuel with a sulfur content of less than 15 parts per million. The combination of diesel particulate filters and ULSD can reduce emissions of hazardous particulates, smog causing hydrocarbons, and poisonous carbon monoxide by 60 to 90%. In fact, it is possible to produce an engine that is cleaner in particulates than a natural gas engine. Furthermore, studies have shown that diesel particulate filters need not cause additional maintenance on bus or truck engines, or create a fuel economy penalty. The proposed DPF here is a filter which has a polymer cell which have more permeability and it will be assumed to have the same porosity as ceramics filters.

LITERATURE REVIEW

In 1994, Peat made an approximation to the effect of mean flow on sound propagation in capillary tubes. The paper began with the derivation of the governing equations by the use of boundary layer approximations. It was shown that these equations reduced to those for the low reduced frequency solution equations in the limit of zero steady flow. (Peat, 1994) In practical, the radial velocity component is retained in the equations under these approximations, even though one might suppose that it would be negligible in a capillary tube. In this study, a first approximation was sought for the effect of the steady flow upon sound propagation in capillary tubes. For simplicity, the background temperature was assumed to remain constant and tubes of circular cross-section were considered. The results given in this paper indicated the effect of steady flow-upon the axial propagation of sound waves in capillary tubes, in terms of both decay rate and phase velocity. In the zero flow limits these factors were the same for both forward and backward propagation waves but, with steady flow, the forward convected waves behaved differently from that of the backward waves, which propagates into the flow. It was also found that a third wave was generated in the steady flow case, unless either the acoustic disturbances were assumed to be isentropic or else the Prandtl number is unity. Dokumaci (1995) studied the sound transmission in narrow pipes with superimposed uniform mean flow and made an acoustic modeling of automobile catalytic converters. The Study was mainly concerned with the acoustic modeling of the honeycomb structure in

automobile catalytic converters, in the large shear wavenumber limit, which was valid for the standard pipes in internal combustion engine exhaust systems; this study provided a useful alternative to the one-dimensional theories. (Dokumaci, 1995) In this study a two-port elements have been presented for the acoustic modeling of the honeycomb structure in monolithic catalytic converters. Also this study predicted a marked frequency dependence model for the honeycomb structure at the lower frequencies. In the same year, Astley and Cumings presented Finite Element Model (FEM) solutions, based on simplified equations for waves in a visco-thermal fluid, for the problem of sound propagation in capillary tubes. They made analysis for the laminar flow with a parabolic velocity distribution and a quadratic cross-section. The simplification of the governing equations is based on that the axial gradients are much smaller than the gradients over the cross-section. They derive the linearized fluid-dynamical differential governing wave motion in a narrow tube containing a viscous, heat-conducting fluid and discussed the boundary conditions that must be applied at the tube walls. (Astley and Cummings, 1995) In 1996, analytical solution have been developed for sound propagation in capillary ducts with mean flow. In this study the transverse of particle velocity, temperature, and viscosity were considered. A fully developed laminar steady flow was assumed and the concept of a complex propagation constant was introduced in the formulation. (Ih *et al.*, 1996) The final equation formed reduces to Kummer-type differential equation and its solution was obtained in terms of confluent hyper geometric functions. The dispersion equation for the complex propagation constants was taken on a recursive form. A simplified form of the analysis permitted comparison with previous results dealing with visco-thermal effects and included the features of Poiseuille-type laminar steady flow for low and medium shear wave numbers. Jeong and Ih (1996) showed by numerical solutions of the governing equations, that including the radial particle velocity has a small but noticeable effect. They made a numerical study on the propagation of sound through capillary tubes with mean flow. They used the general formulations of conservation equations with non-isentropic conditions based on the low reduced frequency solutions, the linearized governing equations were solved by the recursive use of numerical methods. Also they investigated the characteristics of the forward and backward propagation acoustic waves, and the characteristics of the hydrodynamics waves were also investigated when steady flow was present. (Jeong and Ih, 1996) In this study the effect of the radial and axial temperature gradient was excluded.

Dokumaci extended his earlier study to the case of rectangular narrow tubes with a plug flow. The solution procedure is now based on a weak (Galerkin) formulation, where the fields over the channel cross-section are expanded as double Fourier sinus series. The Study presented a comparative study of these for pipes having

circular and rectangular cross-sections. The results indicated that the assumptions of a uniform mean flow profile closely predicted the results based on a parabolic profile. The in-plane velocity terms were retained in this study, and they had been used in the continuity equation. (Dokumaci, 1998) After three year, Dokumaci could derive an approximate dispersion equation for sound waves in a narrow pipe with ambient gradients. The paper presented an approximate solution in which the presence of mean flow, which is assumed to have a uniform velocity profile, was taken into account. The solution also included the effect of constant pressure gradient. A dispersion equation was derived by assuming that the spatial variations of the ambient variables can be lumped (Dokumaci, 2001). Allam and Abom (2002) build up theoretical models to predict the acoustic 2-port (4-pole) of a Diesel Particulate Filter (DPF) unit. In the first model the steady flow resistance was used to calculate an equivalent lumped resistance. In this model the wave propagation in the DPF monolith was neglected and was a low frequency approximation. (Allam and Abom, 2002) To include wave propagation effects the monolith was described using a coupled wave guide model, where the coupling was via the porous walls of the monolith. Darcy's law was used to describe the pressure drop in the porous walls. Based on this an improved theoretical model was obtained, both models were compared to measured data from a test rig with clean air operating at 20°C. The agreement for the 1-D wave propagation model was quite good but for low frequencies (<300 Hz) the lumped resistance model also seems satisfactory. Fairbrother and Tonsa (2003) described work on simulating the acoustic behavior of catalysts and DPF devices using both linear and nonlinear techniques. (Fairbrother and Tonsa, 2003) In this Study two existing computer simulation codes (one linear, one non linear) had been extended and combined into a single package. The linear method was carried out in the frequency domain and made use of plane wave assumptions. By using the transfer matrix method, also called the four pole method. Specific models after treatment components were used to generate transmission loss predictions versus frequency. The non linear method solved the mass, movement and energy equations in the time domain and made use of white noise excitation and Fast Fourier Transforms (FFT) to obtain results in the frequency domain. After that, Allam and Abom (2002) made an acoustic modeling of an After-Treatment Device (ATD). In this study Allam and Abom presented an acoustical model of a complete ATD for a passenger car. The model was built up to four basic elements:

- Conical inlet/outlet
- Straight pipe
- Catalytic Converter (CC) unit
- DPF unit (Allam and Abom, 2003)

For the DPF unit two models had been developed. One simple 1-D model with no influence of wall boundary layers and one based on a CC model suggested by Dokumaci (1998) including wall boundary layers. Both models neglected the effects of chemical reactions. Also they were compared with experimental data and the agreement was satisfactory. In 2003, an investigation was made for the boundary layer induced noise and a method to design trim panels containing a large number of coupled tubes to effectively reduce noise was described. (Wijnant *et al.*, 2003). The theory of viscothermal wave propagation in tubes was discussed. They calculated the absorption coefficient for a panel containing a number of non-coupled tubes. Initial results optimized the tubes' length and radii for a desired fictive absorption coefficient; also the applicability of the method was proved. Allam (2005) was able to study the acoustic modeling and testing of DPF and considered it as an eigenvalue 1D problem. This study presented a first attempt to describe the acoustic behavior of DPFs and to present models which allow the acoustic two-port to be calculated. (Allam and Abom, 2005) The simplest model neglected wave propagation and treated the filter as an equivalent acoustic resistance modeled via a lumped impedance element. This simple model gave a constant frequency independent transmission loss and agreed within 1 dB with measured data on a typical filter (length 250 mm) up to 200-300 Hz (at 20°C). (Allam and Abom, 2005) In the second model, the ceramic filter monolith is described as a system of coupled porous channels carrying plane waves. The coupling between the channels through the porous walls is described via Darcy's law. This model gave a frequency-dependent transmission loss and agreed well with measured data in the entire plane wave range. After that, Allam and Abom successes in modifying the 1-D model using the classical (exact) Kirchhoff solution for a plane wave in a narrow tube. The model was in close agreement with the predictions of the new model. Furthermore this model, which assumed isothermal sound propagation, worked satisfactorily up to 800-1000 Hz for a typical filter at operating (hot) conditions (Allam and Abom, 2006). This study formed the backbone of the presented study, where a 1D linear acoustic model for a DPF unit had been developed.

RESEARCH METHODOLOGY

The study was conducted at the science and nursing faculty at Jerash private university in 2010.

The problem of sound propagation in gas-filled rigid porous media is studied; it can be characterized by a complex-valued gas density and complex-valued gas incompressibility. These two so-called scaling functions are frequency-dependent and governed by the geometry of the pore structure. The former function describes the inertial and viscous interactions between the gas and the

pore space, and the latter one describes the heat exchange effects between the two domains. By assuming wide separation between the characteristic pore size and the wavelength, the porous medium can be characterized by several measurable quantities, like the porosity ϕ , the viscous and thermal permeabilities σ_0 and σ_1 and the viscous and thermal length scales Λ and Λ_t . These are called the macroscopic pore properties, determining the scaling functions. In porous materials (fibrous and granular), the absorption process of the acoustic waves takes place through viscosity and thermal losses of the acoustic energy inside the micro tubes forming the material. This kind of material is widely used in room acoustics, in order to control reverberation time, avoid undesired reflections, fill double wall cavities, floors and ceilings and exhaust gases emission reduction devices (DPF) units. Usually it is assumed that the material has a rigid frame and the fluid filling the medium inside the pores can be considered as homogeneous medium with complex frequency dependent characteristic impedance (Z) and a propagation constant (k). The thermo viscous effects in the fluid filling interstices among the fibers or the particles are responsible for the energy loss of the propagating acoustic wave. Generally, thermal losses are much lower than viscous losses in this kind of material. So, one can neglect the thermal losses of energy. A more sophisticated approach is to perform an analysis of wave propagation in an idealized microstructure corresponding to the form of real materials. For a model of identical, parallel, cylindrical pores, in a rigid frame, there are two distinct methods of analysis: one of which is based upon the idea of a complex or frequency-dependent density for the air within the pores. The other method introduces the idea of a frequency-dependent viscosity operator.

Many theories of acoustical wave propagation in porous media are evolved from an initial conceptual model of a medium containing identical parallel cylindrical capillary pores running normal to the surface. In this thesis there will be more focus on the capillary pore approach for a medium. The frame of which is assumed to be rigid, and an interest with a statement of the results of an analysis of wave motion in a single capillary pore and a consideration for viscous and thermal effects will be taken into accounts. Zwikker and Kosten theory have showed that, at least in the limiting cases of low and high frequency, such independent treatments give the correct results for motion in a viscous, conducting fluid contained within a cylindrical channel, when expressed in terms of a complex density and a complex incompressibility. As they point out, given this results, there is considerable merit (from the point of view of simplicity of derivation), in stating only the independent treatments. In the following sections there will be a description for the physical model, the derivation of governing equations from basic equations (momentum, energy and continuity), the continuity equation is also

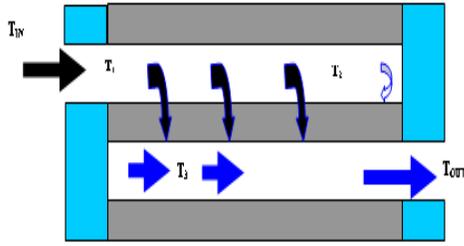


Fig. 2: DPF sections and the 2D flow of gases

written in average form and some results from solving both momentum and energy equations, and from state equations with the help of Darcy's equation are substituted in the average form of continuity equation to get the final tractable linear partial differential equations (by making some complicated mathematical operations), which will be solved by helping of Fourier sinus series to find the propagation constants, and other needed quantities.

Derivation of the governing equations:

Physical model: Figure 2 shows obviously how DPF works and it can be noticed that they started flow is in positive x-direction, but after it enters the filter it flows transversely in y-direction, hence the gas flows in 2-D plan.

The DPF can be manufactured from different materials such as Cordierite or Silicon Carbide, and in its most common form, it consists of a substrate of narrow channels in which each channel is blocked at single end. Adjacent channels have this blockage at alternate ends with this construction exhaust gas may enter at one end. The gas must pass through the permeable wall of a channel before exiting the channel, and is thus termed a wall flow device. For this behavior, it is clear that the flow in y-direction has a considerable effect i.e. the transverse velocity has a vital role and it has an effect in the form of making the problem like as a 2-D problem.

It is worth to mention, the structure of Diesel Particulate Filler (DPF) cells will be considered approximately square in the cross- section with a usual width of (1-2) mm.

In order to develop an acoustic model for the sound propagation in DPF unit after it is connected on the exhaust pipe, the propagation constant for two neighboring cells has to be satisfied inside the filter. To derive the governing equations that describe behavior of sound propagation in the filter and which will help in controlling noise and vibration of the exhaust pipe after DPF unit is connected, the following assumptions have to be taken into account:

- The axial mean flow velocity
- DPF unit will be considered as porous media completely
- The transverse “normal” component of velocity (v) will not be neglected by studying the system as a 2-D model
- Flow in porous DPF unit will be considered as viscous-thermal flow, incompressible, laminar, a steady (axial mean flow) and Newtonian ideal gas flow

Chemical reactions are neglected: As shown in Fig. 2, DPF unit will be split into five areas each described by an acoustic two- port and each one has an acoustic impedance to be calculated, and depending on this splitting of DPF the transfer matrix for filter unit is then can be written as:

$$T_{DPF} = [T_{IN} \ T_1 \ T_2 \ T_3 \ T_{out}] \quad (1)$$

Governing equations derivation: The propagation of sound is always associated with a medium; sound does not propagate in a vacuum. Sound is generated when the medium is dynamically disturbed. Such disturbance of the medium affects its pressure, density, velocity, and temperature.

By applying Eq. (1) and take all terms of the matrix T_{DPF} in series and then applying Eq. in [2] the resulted quantity is known as the transmission losses, which can be given as [2].

$$TL_{DPF} = 10 \log_{10} (| (1/16)T_{11} + (1/8)iY_1NT_{21} + (1/8)NT_{21}Z_{IN}M_{IN}(1/m_{IN}^2 - 1) + (1/4)T_{11}Z_{OUT}M_{OUT}(1-1/m_{OUT}) + (1/2)iY_1NT_{21} + 0.5NT_{21}Z_{IN}M_{IN}(1/m_{IN}^2 - 1) + Z_{OUT}M_{OUT}(1-1/m_{OUT}) + (1/8)iY_3T_{11} - 0.25Y_3Y_1NT_{21} + 0.25iY_3NT_{21}Z_{IN}M_{IN}(1/m_{IN}^2 - 1) + (1/16)T_{12}NiY_3 - (1/8)Y_1Y_3T_{22} + (1/8)iY_3T_{22}Z_{IN}M_{IN}(1/m_{IN}^2 - 1) + (1/16)NT_{21} + 0.25NT_{21}Z_{OUT}M_{OUT}(1-1/m_{OUT}) + (1/8)NT_{21}iY_3 + (1/16)T_{22}|) \quad (2)$$

where,

- Y1: The plug mass impedance of section 1 ($Y_1 = i\rho\omega l_1/d_{hj}^2N$)
- Y3: The plug mass impedance of section3 ($Y_3 = i\rho\omega l_3/d_{hj}^2N$)

RESULTS AND DISCUSSION

Two-dimensional acoustic models have been built to study the sound propagation in DPF unit under two cases, under the first case, the parameters: pressure, temperature, density, and velocities were considered to be time harmonic variables, which gave a modified four-port (2-D) acoustic model. The solution of eigenvalue problem of this model gave four roots, then transmission losses have been calculated. The result have been represented as the Fig. 3 and 4. Figure 3 Transmission losses against frequency under the case of cold conditions (Without soot layer), and Mach = 0.02.

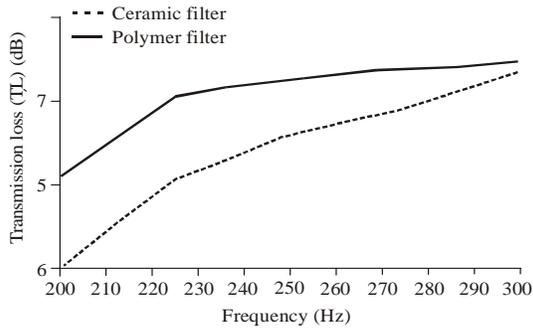


Fig. 3: Transmission losses against frequency under the case of cold conditions (Without soot layer) and Mach = 0.02

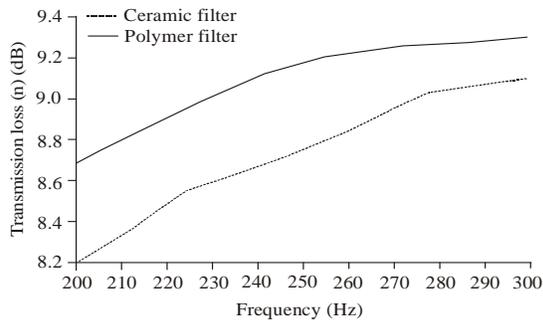


Fig. 4: Transmission Losses (TL) against frequency (w) under the case of cold conditions (With soot layer), Mach = 0.02, and for typical filter

Figure 3 shows the Transmission Losses (TL) against the frequency under the case of time harmonic variation for the typical filter with no soot layer and for cold conditions. As shown in this figure the transmission losses are increased with frequency because transmission losses are proportional with frequency, this is obvious from the final mathematical relationship. By comparing TL of the proposed study with that of ceramics filters it can be noticed that there is an improvement in the proposed model, the more TL the more noise reduction. The reason that TL values for the proposed model are higher than that given for ceramics filters is that the proposed study deals with the flow of gases emission as a 2-D flow and so the flow in y-direction is not negligible as in last studies, hence TL can be of a noticeable value in y-direction. At $w = 300$ Hz it can be noticed that there is a good agreement between the two studies.

Secondly the parameters are assumed to be harmonic in time and in 2-D space, at this stage a six-port acoustic model has been invented since six roots and six corresponding eigenvectors are resulted. Figure 4 describes TL for the typical filter with soot layer compared with that of Allam's results at Mach = 0.02. (Allam and Abom, 2006) It can be noticed from this figure that there is a good agreement in the behavior of the two studies, but the TL for the proposed study is

higher than that of Allam's one, but a more agreement at higher frequency is achieved.

CONCLUSION

The resultant waves propagate through the DPF unit depend on two factors; attenuation shift and phase shift, where both of them damped as shear wave number.

Both transmission losses and Noise Reduction Factor (NRF) for the diesel particulate filters DPF are proportional to frequency where they are increasing as frequency is increased with noting that the transmission losses at the case of existing soot layer are higher than those with no soot layer.

The transmission losses and the Noise Reduction Factor (NRF) are improved in the case of using polymer in Diesel Particulate Filter DPF.

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