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An Electrical Capacitance Based Measurement Method for Soot Load Estimation in a Diesel Particulate Filter

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Abstract: This paper presents a novel approach of Particulate Material (soot) measurement in a Diesel particulate filter using Electrical Capacitance Tomography. Modern Diesel Engines are equipped with Diesel Particulate Filters (DPF's), as well as on-board technologies to evaluate the status of DPF because complete knowledge of DPF soot loading is very critical for robust efficient operation of the engine exhaust after treatment system. In course of time, soot will be deposited inside the DPFs which tend to clog the filter and hence generate a back pressure in the exhaust system, negatively impacting the fuel efficiency. To remove the soot build-up, regeneration (active or passive) of the DPF must be done as an engine exhaust after treatment process at pre-determined time intervals. Since the regeneration process consume fuel, a robust and efficient operation based on accurate knowledge of the particulate matter deposit (or soot load) becomes essential in order to keep the fuel consumption at a minimum. In this paper, we propose a sensing method for a DPF that can accurately measure in-situ soot load using Electrical Capacitance Tomography (ECT). Simulation results show that the proposed method offers an effective way to accurately estimate the soot load in DPF. A hardware-in-loop bench has been built to further develop this sensing concept and experimentally verify the associated measurement technology. Preliminary experimental data is very promising. The proposed method is expected to have a profound impact in improving overall PM filtering efficiency (and thereby fuel efficiency), and durability of a Diesel Particulate Filter (DPF) through appropriate closed loop regeneration operation.

1. INTRODUCTION

Particulate matter also known as particle pollution or soot is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles. The size of particles is directly linked to their potential for causing health problems. EPA is concerned about particles that are 10 micrometres in diameter or smaller because those are the particles that generally pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects.

The issues of global climatic changes and human health hazards caused by different types of pollutions led environment protection agencies to identify the scopes of improvement and make the regulations more rigorous day by day. With increasingly stringent emission regulations novel diesel engines have come a long way in the area of emission control technologies in the reduction of particulate matter emissions via diesel particulate filter or DPF.

Diesel particulate filters were first used in the 1980's which remove the particulate matter/ soot from the exhaust of the Diesel engine with an efficiency level of 90% or more. The most commonly used DPFs are porous ceramic wall-flow filters, shown schematically in Fischerauer et al. Refractory materials such as Silicon Carbide, Cordierite or Aluminum-Titanate are used for this purpose (Twigg et al, 2009). Silicon carbide filters dominate the market owing to the material's mechanical strength and high thermal stability (Joerg Adler, 2005). Alternate channels are plugged, forcing the exhaust through the porous channel walls. The gaseous exhaust passes through the porous walls, but PM is trapped in the filter.

However, as the PM or soot is retained by the filter, the filter passageway increasingly becomes more restrictive resulting in elevated back pressure in the exhaust. This furthers results in lower fuel efficiency for the engines since the pistons have to exert more pressure to purge the exhaust gas. One effective way to address this problem is to burn the soot load in the DPF periodically either by injecting more fuel in the engine or by a separate combustor upstream of the DPF with the aid of a diesel oxidation catalyst (DOC). The latter which is known as active regeneration of DPF is more efficient and is commonly used for DPF. Here a fuel doser is used to raise the exhaust gas temperature to burn off the soot load in DPF. The timing and amount of fuel dosing is critical in ensuring optimal performance of DPF functions. Current DPF particulate matter detection methods are not likely to be suitable for meeting the stricter requirements as indicated in Husted et al, 2012.

The performance efficiency of a DPF with active regeneration is largely dependent on the accuracy of soot load estimation. Current soot load estimation is based on differential pressure measurement across the DPF whose accuracy can vary up to ±50% from the true soot load (Sappok et al, 2010). As a result, fuel dosing for active regeneration may not be optimal. It has been shown that fuel penalty caused by regeneration (2.2% to 5.3 %) is more than fuel penalty due to backpressure (1.5% to 2.0 %) (Sappok et al, 2010). Accurate soot load knowledge is also necessary if one wants to rule out possible overheating of the DPF caused by exothermic soot oxidation. Because if DPF is allowed to accumulate too much particulate matter, the large amount of heat released upon regeneration cannot effectively be dissipated, resulting filter damage such as by the formation of cracks or regions which may be locally melted.

The knowledge of the tomography of DPF is a very important to minimize the impact of fuel consumption and avoid damaging the filter and other after treatment systems. In this paper we present a novel instantaneous soot load sensor based on electrical capacitance that can improve the soot load estimation. This sensor can be used in the feedback loop to improve the soot load estimation allowing for correct amount of fuel injection upstream of diesel oxidation catalyst (DOC) and thus potentially improving the overall DPF performance. For this reason we have explored the designing, building, and implementing a feedback control system for an actively regenerated DPF based on real-time electrical capacitance soot load sensor feedback and presented it here for the first time.

2. BASICS OF ELECTRICAL CAPACITANCE TOMOGRAPHY (ECT) TECHNOLOGY

2.1 Permittivity model

When two parallel plates of a conducting material separated by an air gap have been connected and a voltage has been applied then electrons are drawn from the upper plate through the resistor to the positive terminal of the battery. This action creates capacitance. This element is called a capacitor (Robert L. Boylestad). And capacitance can be defined as

$$C = \varepsilon_o \varepsilon_r \frac{A}{d} \qquad (1)$$

Based on above mentioned principle Electrical capacitance tomography (ECT) system been established.

The capacitance measured depends on the relative permittivity of the materials between the electrodes. Their relation can be linear or nonlinear in nature. It depends on the permittivity models used to characterize the way in which the contents occur. The various permittivity models used are the series model, parallel model, and Maxwell's model.

Suppose one substance of relative permittivity εr and air mixed together. That substance occupy x% of the total space between two electrodes. (S. S. Donthi, 2004)

When two components in the pipe lie on top of one another then the effective capacitance can be considered as two capacitances connected in series. This is illustrated in fig. 1and the capacitance and permittivity are related in a nonlinear fashion. The effective permittivity and overall capacitance is given respectively in following equations.

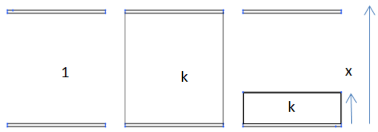

Fig. 1. Empty, completely filled & partially filled.

$$\varepsilon_s = \frac{\varepsilon_r \varepsilon_o x(1-x)}{1 - x(\varepsilon_r - 1)} \ \& \ C_s = {A\varepsilon_s}/{d} \qquad (1)$$

Again two components in the pipe appear side by side manner; their effective capacitance can be considered as two capacitances connected in parallel. This is illustrated in fig. 2 and the capacitance and permittivity are related linearly. The effective permittivity and overall capacitance is given respectively in following equations.

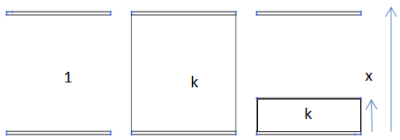

Fig. 2. Empty, completely filled & partially filled.

$$\varepsilon_p = \varepsilon_o[1 + x(\varepsilon_r - 1)] \ \& \ C_p = {A\varepsilon_p}/{d} \qquad (1)$$

Finally the generalized Maxwell Garnett mixing formula for multiphase mixtures with randomly oriented ellipsoidal inclusions in equation (5) and equation (6). (Koledintseva et al, 2006)

$$\varepsilon_m = \varepsilon_b + \frac{\frac{1}{3}\sum_{i=1}^{n} f_i(\varepsilon_i - \varepsilon_b)\sum_{k=3}^{3}\frac{\varepsilon_b}{\varepsilon_b + N_{ik}(\varepsilon_b - \varepsilon_b)}}{1 - \frac{1}{3}\sum_{i=1}^{n} f_i(\varepsilon_i - \varepsilon_b)\sum_{k=3}^{3}\frac{\varepsilon_b}{\varepsilon_b + N_{ik}(\varepsilon_b - \varepsilon_b)}} \ \& \ C_s = {A\varepsilon_s}/{d} \qquad (1)$$

2.2 ECT measurement principle

ECT is used to obtain information about the spatial distribution of a mixture of dielectric materials inside a vessel, by measuring the electrical capacitances between sets of electrodes placed around its periphery and converting these measurements into an image or graph showing the distribution of permittivity. The images are approximate and of relatively low resolution, but they can be generated at relatively high speeds.

ECT can be used with any arbitrary mixture of different non-conducting dielectric materials such as plastics, hydrocarbons, sand or glass. However, an important application of ECT is viewing and measuring the spatial distribution of a mixture of two different dielectric materials (a two-phase mixture), as in this case, the concentration distribution of the two components over the cross-section of the vessel can be obtained from the permittivity distribution.

An ECT system consists of a capacitance sensor, Capacitance Measurement Unit (CMU) and a control computer. For imaging a single vessel type with a fixed cross-section and with a fixed electrode configuration, the measurement circuitry can be integrated into the sensor and the measurement circuits can be connected directly to the sensor electrodes. This simplifies the measurement of inter-electrode capacitances and is potentially a good design solution for standardized industrial sensors.

However, most current applications for ECT are in the research sector, where it is preferable to have a standard capacitance measuring unit which can be used with a wide range of sensors. In this case, screened cables connect the sensor to the measurement circuitry, which must be able to measure very small inter-electrode capacitances, of the order of 10-15 F (1 fF), in the presence of much larger capacitances to earth of the order of 200,000 fF (mainly due to the screened cables).

Basically ECT system is a set of capacitor plates placed around a pipe or any other vessel. A source voltage is applied between one electrode (the source electrode) and ground and the resulting currents flow between the source electrode and the remaining (detector) electrodes to ground are measured. These currents are directly proportional to the capacitances between the source and detector electrodes. The set of capacitance measurements made.

In ECT a complete set of measurement projections is made by exciting each electrode in turn as a source electrode and measuring the currents which flow into the remaining detector electrodes. So for an 8-electrode sensor, as shown in fig. 3 there will be 8 x 7 = 56 possible capacitance measurements. However, as half of these will be reciprocal measurements (the same capacitance should be measured by exciting electrode 1 as a source and measuring the current into electrode 2 as is obtained by exciting electrode 2 as a source and measuring the current into electrode 1 etc.), there will only be 28 unique capacitance measurements for a complete set of projections. In general for a sensor with E electrodes, there will be E*(E-1)/2 unique capacitance measurements.

Fig.3. Empty, completely filled & partially filled.

The set of measured inter-electrode capacitance values and subsequently obtained permittivity's are normalized to construct the permittivity images.

Capacitance normalize $C_n = \frac{C_i - C_i(emp)}{C_i(full) - C_i(emp)} 0 < C_n < 1$.

Permittivity normalize $K_n = \frac{K_i - K_i(emp)}{K_i(full) - K_i(emp)} 0 < K_n < 1$.

The normalized values are then projected into a square pixel grid where the pixel values are similarly normalized to lie between 0 to1. The image formed is not an exact solution but an approximate solution.

2.4 Detection image formation

The permittivity image or soot detection images are mapped onto a square pixel grid. The complete set of a measured inter-electrode capacitance values is required to reconstruct one permittivity distribution image. Fig. 4 shows a 16*16 square pixel grid used to display the permittivity distribution image of a 4-electrode sensor having circular intersection of Diesel particulate filter. From this (16*16) square pixel grid containing 256 pixels, only 210(approx.) are needed to construct the cross sectional image of the DPF and remaining pixels are not required and hence neglected.

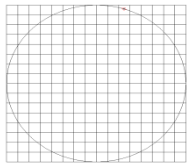

Fig. 4. Empty, completely filled & partially filled.

The field lines between two plates are curved and to suit the requirement these lines can be approximated. A proper sensitivity map, purpose of which is to aid in selecting the proper pixel that individually contributes to the capacitance changes, have to be developed for visualizing the electric field established between two electrodes when one of them is excited.

A simple procedure for reconstructing an image of an unknown permittivity distribution inside the sensor from the capacitance measurements is the Linear Back Projection (LBP) algorithm. LBP method will be chosen for future complete tomographic image generation but this paper focuses only on the detection image generation of soot accumulation.

Let us consider an x-electrode sensor and square pixel grid pixel number is N. A grey level K(N) for each pixel has been calculated based on following fig. 5.

$V_{AB}+V_{AC}/4+V_{BD}/4$ (A)	$V_{AD}+V_{AC}/4+V_{BD}/4$ (B)
$V_{BC}+V_{AC}/4+V_{BD}/4$ (C)	$V_{CD}+V_{AC}/4+V_{BD}/4$ (D)

Fig. 5. Empty, completely filled & partially filled.

The relationship between capacitance permittivity distributions can be approximated and written in a normalized form as:

$$K(N) = \frac{\sum_{i=0}^{m} C_i S_i(N)}{\sum_{i=0}^{m} S_i(N)} \quad (1)$$

In principle, once the set of inter-electrode capacitances C have been measured and normalized, the permittivity distribution K can be obtained from equation used in figure 6.

From previous relationship it's visible that the C matrix can directly transform into a 2*2 pixel matrix where the change in soot deposition will be reflected.

Direct contributions of pixels to the measured capacitance between any specific electrode-pair is not be specified, but it can be shown from the image that certain pixels have more effect than others on this capacitance. Consequently, component values allocated to each pixel proportional to the product of the electrode-pair capacitance for this electrode-pair.

This process is repeated for each electrode-pair capacitance in turn and the component values obtained for each pixel are summed for the complete range of electrode-pairs.

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3. SIMULATION RESULT

If Study conducted by Michel et al, 1993, shown that in microwave range dielectric constant of soot has dependency on the soot layer thickness.

In this model series permittivity model has been chosen to calculate the effective permittivity of soot and air mixture. The model length set at 6 inch, so the length of the capacitor plate will be 6 inch and for 4 capacitor plate ECT sensor the width of the capacitor plate will be 4.71 inch (approx.) and maximum distance between two plates will be 5.6 inch. So

$$\varepsilon_s = \frac{5 \times 8.854 \times 10^{-12} \times (1-2)}{1-2(5-1)} = 1.2649 \times 10^{-11}$$

$$C_s = 6 \times 4.72 \times 1.2649 \times 10^{-11} / 5.6 = 63.8301$$

A model of the soot detection system has been designed in PSpice to check the detection voltage. An Ac 5 volt 1 MHz has been supplied for 2 different (randomly pick) types of capacitance values 60 pF (fig. 7, 8), 90 and 130pF and output voltage has been checked. Results are shown in table 1 and fig. 6.

Table 1. Output voltage for different capacitance values

Input voltage	Capacitance	Output voltage
5 Vac	60pF	1.6-1.7v
5 Vac	70pF	1.2-1.3v
5 Vac	90pF	0.9-1.0v
5 Vac	110pF	0.7-0.8v
5 Vac	130pF	0.5-0.6v
5 Vac	150pF	0.3-0.4v

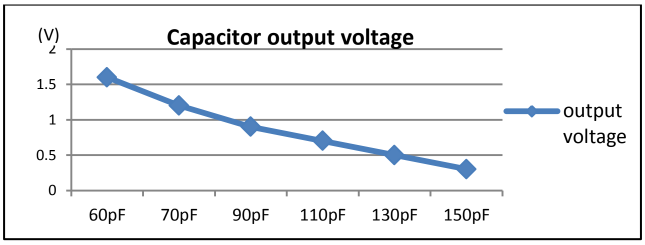

Fig. 6. Empty, completely filled & partially filled.

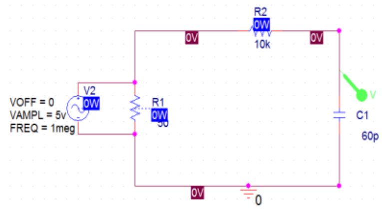

Fig. 7. Empty, completely filled & partially filled.

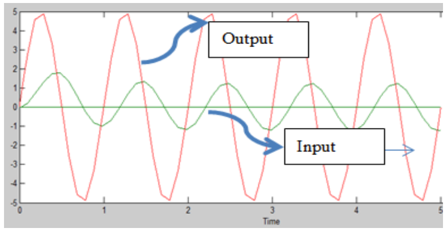

Fig. 8. Empty, completely filled & partially filled.

Above simulation results showed that even a very small amount of soot deposition causes variation on the output voltage. Applying these capacitance values and voltage values in linear back projection algorithm will help to build the tomographic information of a DPF.

4. EXPERIMENTAL SETUP

The experimentation of soot measuring system using ECT is going on in an experimental model of DPF made of Nylon 66. This nylon 66 has very close dielectric properties of conventional DPF made from cordierite which has dielectric property of 4.7(approx.) in 1MHz.

The DPF outer shell wall is conductive so the ECT system electrode has to be placed inside of the DPF wall. In that case the components of capacitance due to the electric field inside the sensor will always increase in proportion to the material permittivity when a higher permittivity material is introduced inside the sensor.

The internal temperature of DPF will be highest when the regeneration of soot is taking place. Regeneration is a process of soot removal from the DPF and there are two different approaches existed one is active and another is passive. Active systems use extra fuel, whether through burning to heat the DPF, or providing extra power to the DPF's electrical system. This process required 600°C to burn Diesel particulate matter. This temperature can be reduced to somewhere in the range of 350°C to 450°C by use of a fuel borne catalyst [2]. There is a more effective way to burn soot at lower temperature brought by Johnson Matthey's novel two-component design [2]. In this novel approach the catalyst is positioned before the filter to convert NO into NO2. The

NO2 then oxidizes the soot that is collected on the filter to regenerate the filter. The soot is combusted at a much lower temperature than is normally required. In fact, the CRT-continuously regenerating technology enables the filter to be regenerated at a temperature that is 20% lower than other filters on the market. By using this approach the soot burning temperature can be reduced up to 240°C. So whatever material we are using as ECT electrode it has to be able to withstand a versatile range of temperature. The properties that led us to choose copper as ECT electrode are [Pryuor et al].

1) Melting point at 1357°K or 1084°C
2) Do not reacted with water
3) Resistivity= $1.68 \times 10^{-8} (\Omega \bullet m)$ at 20 °C
4) Conductivity= $5.96 \times 10^{7} (S/m)$ at 20 °C
5) Temperature coefficient= $0.003862 \ (K^{-1})$
6) Copper resists corrosion from moisture, humidity and industrial pollution

Due to very low temperature coefficient of copper the change of conductivity with the change of temperature will be very low. If the assumption made that the temperature change inside of DPF is linear then relationship between resistivity and temperature will be $\rho(T) = \rho_o[1 + \alpha(T - T_o)]$

T0 is the room temperature. If the temperature T become 300°C then $\rho(T) = 3.489 \times 10^{-8} (\Omega \bullet m)$

Fig.9. shows an isometric view of the experimental setup with 8 capacitance electrodes and DPF model of 152mm (6 in) length with 130mm (5 in) diameter. There is a trade-off has to be done to choose the number of electrode. Higher number of electrode means complicated and expensive data acquisition hardware, smaller capacitance to be measured; slower data acquisition as we can see from papers of Yang et al, 2005 and currently 8-12 numbers of electrodes are commonly used in an ECT sensor. These 8 electrodes have to be placed around the DPF.

A common practice for the length of the ECT sensor is diameter has to be smaller than the length to avoid serious fringe effect (Yang 1010). So if the DPF diameter size is larger than the length then fringe effect cannot be ignored. For experimental purpose in this paper the filter model used with typical dimensions of 130mm (5in.) diameter and 152mm (6in.) length (Pyzik et al, 2005).

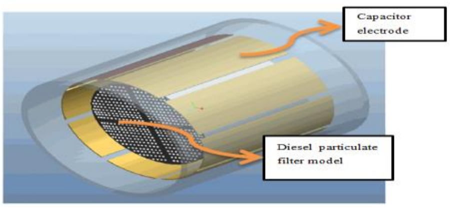

Fig. 9. Empty, completely filled & partially filled.

The test bench is equipped with an automatic National instruments data acquisition system NI DAQ-6008 for capturing the capacitance values. Research team is using dry sand as a replacement of soot to verify the approach of using Electrical capacitance tomography to soot detection. Two different methods of sand distribution have been considered while conducting the experiments. In concentrated distribution the assumption is at first sand start accumulation near to one particular electrode, and later filled up the whole filter. On the other hand in normal distribution the assumption is the sand distributed equally through the whole filter. Data acquisition hardware senses the change of sand accumulation by the changes of the capacitance plate voltages. Voltage signals were processed in LABVIEW and fig. 10 and fig. 11 are depicting the fact that with the increase of sand accumulation the voltage is also changing. Fig. 12 shows the complete experimental setup to identify the relationship between output voltage and amount of accumulated material.

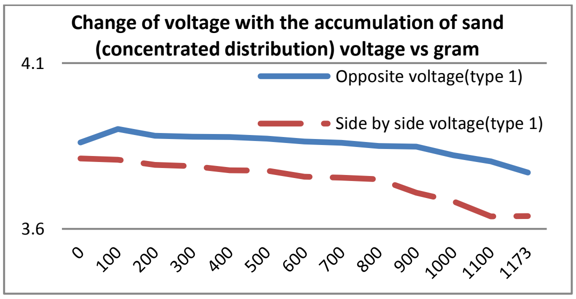

Fig. 10. Change of voltage with the accumulation of sand (concentrated distribution).

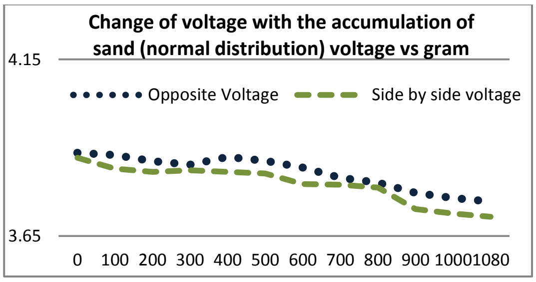

Fig. 11. Change of voltage with the accumulation of sand (normal distribution).

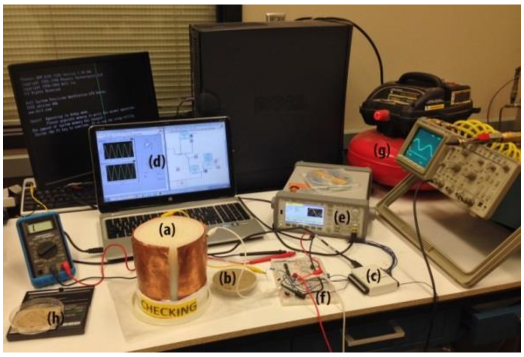

Fig. 12. Experimental setup; (a) filter model, (b)sand as soot replacement, (c) NI DAQ, (d)Data acquisition program, (e)Signal generator, (f)Data acquisition circuit, (g)Blower, (h) material weighing.

5. EXPERIMENTAL RESULTS

A completing set of experimentation has been conducted on the test bench using sand (density 1.6-1.9 g/cm3) as soot model, nylon 6/6 as DPF model and four copper electrodes. Electrodes will be arranged like fig 19.

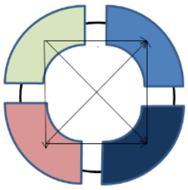

Fig. 13. Four electrode arrangement.

Sand has been poured into the grooves of DPF in a uniform fashion and simultaneously capacitance voltages between A-B VAB, A-C VAC, A-D VAD, B-C VBC, B-D VBD and C-D VCD has been measured using the NI DAQ-6008 device.

Now to prepare the soot detection image we need to consider a 2 by 2 pixel matrix. To assign the value of each pixel we need to normalize the capacitance voltage value. Every pixel will have certain normalize capacitance voltage values like figure 6.

Based on the mathematical relationship portrays on Fig 14 each pixel values can be evaluated. Considering a scenario where DPF model is 25% fill means total fill is 300 gm. According to fig 17 and voltage values from table 3 pixel values of A pixel is calculated below:

A pixel value= VAB+VAC/4+VBD/4= 3.9656 + 3.9549/4 + 3.87556/4 = 5.923215

Using this pixel values detection image has been generated. Fig 15 and 16 depicts some stages of soot deposition image.

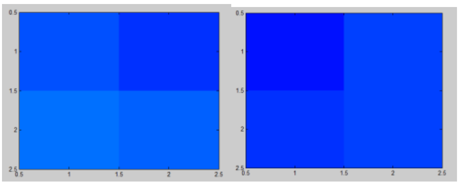

Fig. 14. (a) DPF zero fill (b) DPF 25% fill

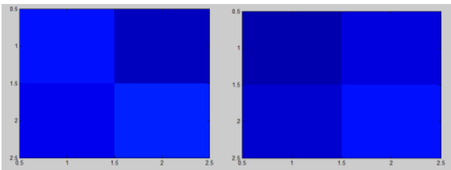

Fig. 15. (a) DPF 50% fill (b) DPF 75% fill

6. CONCLUSIONS

This paper presents a novel approach of soot load measurement in a Diesel particulate filter using Electrical Capacitance Tomography. The proposed sensing method for a DPF is able to measure in-situ soot load as indicated by the simulation results. The simulation results demonstrated the general relationship between the amount of soot deposited and the output voltage of ECT system. A hardware-in-loop bench has been built to further develop this sensing concept and experimentally verify the associated measurement technology. Preliminary experimental results show that the ECT based soot load sensing system is responsive to the change in material accumulation thickness.

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