Microwave Plasma System Design and Modelling for Marine Diesel Exhaust Gas Abatement of NOx and SOx

N. Manivannan, W. Balachandran, R. Beleca, and M. Abbod

Abstract—**A set of procedures for the design of microwave based non-thermal plasma reactor for the abatement of NOx and SOx from marine exhaust gas is presented in this paper. The design is supported by finite element based analysis developed in COMSOL multi-physics environment. The proposed design suggests that use of rightly chosen slots arrangements for the insertion of microwave energy into the multi-mode cavity can increase the supplied dosage of microwave energy to the gas.**

Index Terms—**Non-thermal plasma, marine diesel exhausts gas abatement, microwave plasma reactors.**

I. INTRODUCTION

Marine diesel engine flue contains toxic gases such as $NOx(NO+NO_2)$ and $Sox(SO_2)$ which are harmful to environment and health [1]. Marine industry is responsible for more than15%of the world toxic gas emission and its impact can not only affect the coastal area but also extends to large portion of in-land. Treating these gases before releasing into air is not only vital but also regulated by International Maritime Organization (IMO) [2]. The current state-of-the-art of NOx and SOx removal in marineexhaust gas requires two separate units which are space ineffective and cost ineffective [3]. Even though their removal efficiency of SOx is very high (>90%), NOx is relatively low (~70%) which needs to be improved to comply with the requirements set by IMO.

Non-Thermal Plasma (NTP) is an emerging technology for abatement of NOx and SOx of gaseous emissions from diesel engine exhaust. The fundamental nature of non-thermal plasma is that the electron temperature is much higher than that of the gas temperature, including vibration and rotational temperature of the molecules. The electron energy is consumed in the ionisation, excitation and dissociation of the molecules and finally in the formation of active free radicals such as OH, O, N and H. These radicals oxidise SO_2 and NO to SO_3 and NO_2, which then reacts with water vapour present in the exhaust gas forming H_2SO_4 and HNO_3 respectively, and break VOC bonds promoting their conversion to CO and CO_2. Non-thermal plasma reactors can also be used as particulate trap and to remove pollutant gases of NOx and SOx. There are three methods for generating non-thermal plasma in atmospheric gas pressure containing pollutants, namely electron beam (EB) radiation, Microwave (MW) radiation and Electrical Discharge (DC, AC and pulsed field) techniques.

The use of MW irradiation on their own are viable and promising methods for diesel exhaust gas cleaning in view of the reduction of power consumption of the gas treatment process. The absence of internal electrodes removes a source of contamination and makes the reaction chamber simpler compared to electrical discharge methods. In this study we use MW irradiation due to their inherent advantages stated above and to minimise the total energy requirements. It is reported in our previous study that kinetics of NTP allows removal of NOx and SOx very effective to almost 100% for the mean electron energy of 1-3eV [4].

In this paper, the basic design of microwave system to generate plasma is presented. COMSOL Multi-physics based model was developed to calculate the electric field distribution generated by the MW within the non-thermal plasma reactor (NTPR). This model will also be used to determine the locations and orientation of the slots on the wave guide, which is used to launch the MW into the NTPR. The MW launched into the reactor significantly enhances the density of electrons in the reactor to complete the radical formation in the NOx and SOx abatement process.

A. MW Plasma Generation in a Commercial Microwave Oven

In our lab-scale experiments, a commercial microwave oven was used to generate MW plasma. Fig. 1 shows the experimental set-up used.
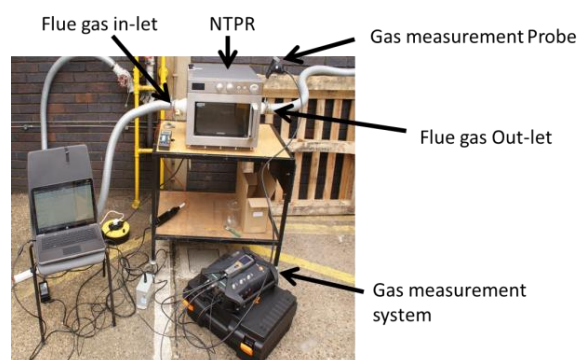

Fig. 1. Commercial microwave oven based plasma generation.

Testo gas analyser was used to measure the concentration of the NOx and SOx in the flu gas with and without the treatment of MW based NTPR. The reduction rate of SOx is very high (>99%) and NOx is moderate (85%) for the flue flow rate up to 20l/s. There are so many limiting factors in using commercial microwave oven for plasma generation; the main ones are very little control over the microwave power, pulsed nature of the magnetrons (so only fraction of the flue gas exposed to the MW) and commercial

microwave is aimed for cooking and energy is focused towards the centre of the rotating dish. So it was really important to design and build our own microwave system which should be in continuous mode of operation, homogenous power distribution, have a complete power management system with power measurement meter (forward and reflected), built with water load for cooling and scalable for high flue gas flow rate.

II. DESIGN OF MICROWAVE PLASMA SYSTEM

Microwave plasma system should consist of microwave generation source (magnetrons), microwave waveguides, microwave multimode cavity, impedance tuning mechanism, microwave measurement and cooling mechanism. Magnetron converts the electrical energy into MW energy, which is then transferred to multimode cavity through waveguides. Plasma treatment of gas is achieved in multimode cavity, where MW energy is used to generate the plasma.

Rectangular waveguides support E-M waves over a certain frequency band, depending on the cross-sectional dimensions. The bigger the cross-section of the waveguide, the lower in frequency it supports. The mode of waveguide is based on two-dimensional fields as transverse magnetic (TM), transverse electric (TE) or transverse electric and magnetic (TEM) according to Electric filed (E-Field) or Magnetic Field (H-Field) is transverse to the direction of propagation (or decay).

The cut-off frequency $(f_c)_{m,n}$ of waveguide of transverse electric field with mode m, n (TE$_{mn}$) can be calculated from,

$$(f_c)_{m,n} = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \qquad (1)$$

where c is the speed of light and a and b are the length and cross-section of the waveguide. The very basic mode of transmission is TE$_{10}$ or TM$_{10}$. Since we are interested in the electric field, which induces the electron energy in the plasma generation, TE model is only considered in this work. The minimum value of the length 'a_{min}' can be calculated using equation (1) for the microwave frequency of 2.45GHzand presented in Table I.

TABLE I: MINIMUM VALUE OF 'A' FOR TE$_{m0}$

Wave Guide mode	m	n	a_{min} (mm)
TE$_{10}$	1	0	62.2
TE$_{20}$	2	0	124.4
TE$_{30}$	3	0	186.6

As can be noticed a_{min} is multiple of half-wavelength of the cut-off frequency of 2.45 GHz (124.4mm) and the length 'b' is ignored in the table as they can be any value less than 62.2mm. It is generally a common practice to use the basic TE$_{10}$ mode for propagating microwave for generating plasma [5], [6]. Standard commercially available waveguides are specified in 'WR' numbers (US systems). There are two types of commercially available rectangular waveguides suitable for our frequency (2.45GHz) and support TE$_{10}$ mode; WR340 and WR430. The interior of these waveguides maintain an aspect ratio of 2:1. Table II

shows a set of details of these waveguides. The operating frequency is the optimized frequency range to operate at low power loss, whereas cut-off frequency is the theoretical minimum frequency the waveguide can support.

TABLE II: THE BASIC PROPERTIES OF WR430 AND WR34

Type	Cross section (mm)	Operating frequency (GHz)	fc (GHz)	λ_c (mm)
WR430	109.22 ×54.61	1.70 to 2.60	1.37	219.0
WR340	86.36 ×43.18	2.20 to 3.30	1.73	173.4

A. Slots

Microwave energy can efficiently be inserted into the NTPR through a number of slots in waveguide arrangements [5], [7].
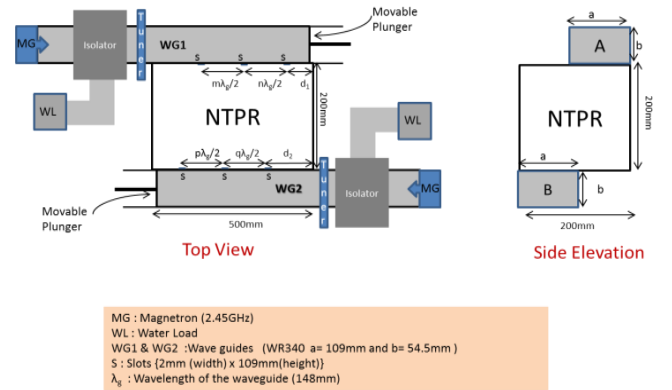

Fig. 2. Schematic of microwave system for the plasma generation.

A new NTPR designed with two magnetrons is shown in Fig. 2. As shown, MW energy is launched into the NTPR through wave guides (WG1 and WG2). The two magnetrons (MG) are connected to their respective waveguides through isolators and tuners. Isolator basically separates the forward MW power and reflected MW power to prevent the magnetrons getting damaged due to the reflected MW power. Isolator transfers the reflected power into the water load, where the MW power gets dissipated. Tuner is placed between the isolator and the wave guide and it allows the impedance of the applicator to be matched with the impedance of the source so that maximum MW energy is transferred to the applicator. In our case applicator is the NTPR. Movable punchers are used to adjust the electric filed distribution pattern within the waveguides in order to find the electric filed peaks in the wave guide where slots need to be located.

III. MICROWAVE SYSTEM MODELLING

Fig. 3(a) shows the integrated Finite Element (FE) model of NTPR with the wave guides according to the schematic shown in Fig. 2. The objective of the design is that the electric field is distributed in an optimum manner within the reactor. The model has two waveguides (WR340: 109mm×55mm), which are attached to the reactor, whose dimensions are 200mm (width) by 200mm (height) by 500mm(length). One waveguide is located at the top of one side of the reactor and the other waveguide is located at the

bottom of the opposite side of the reactor. The magnetrons are represented as rectangular ports and isolator, tuner and water load are ignored as they would not affect the electric filed distribution pattern in the reactor. The plunger operation is modelled by changing the length of the waveguide. There are three slots on each waveguide and they are separated by multiples of half wavelength, λ_g, which is calculated from the following equation:
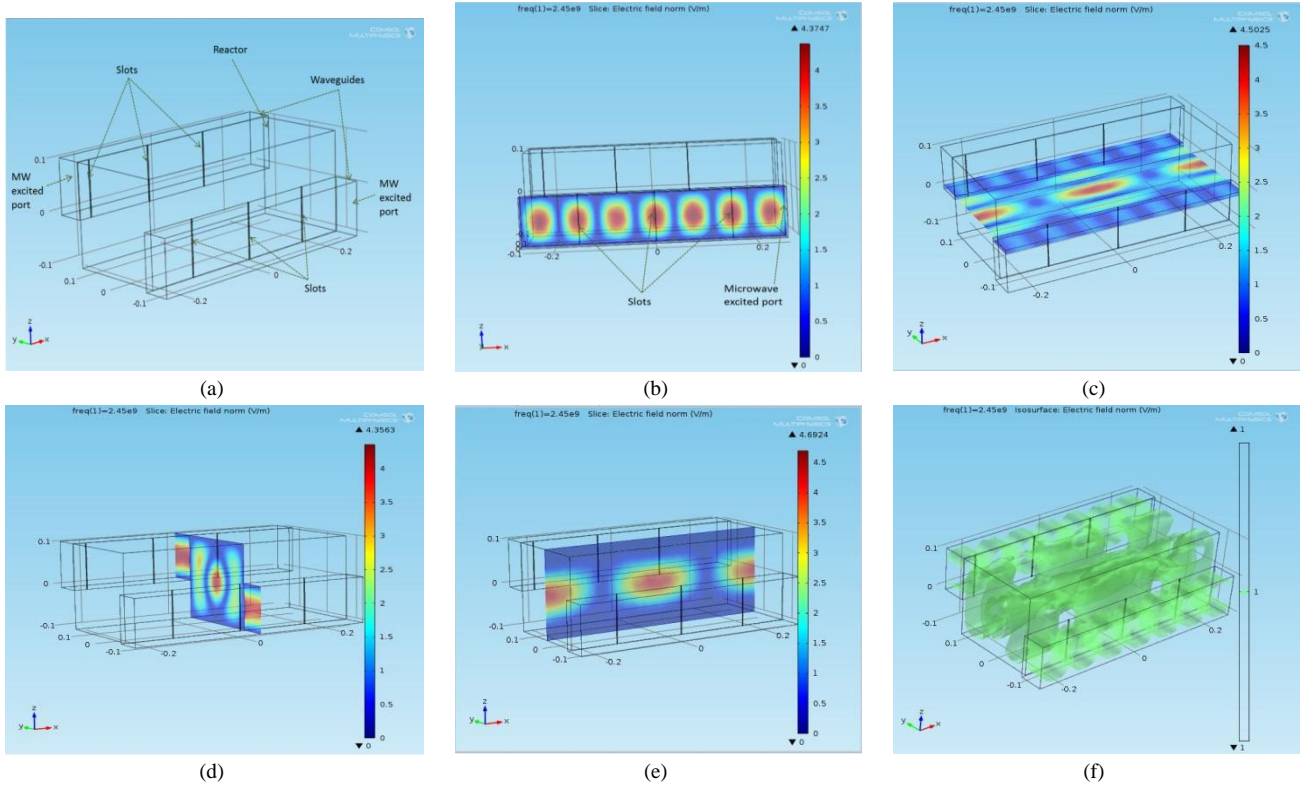

Fig. 3. Results of FEM simulation using COMSOL (a) Geometry of waveguide and reactor and Electric field distribution (b) in the wave guide, showing the locations of the three slots and in the NTPR (c) x-y plane (d) y-z plane, (e) x-z plane and (f) 3D isosurface plot.

$$\lambda_g = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2}} \qquad (2)$$

λ_o = wavelength of microwave used

a = length of the rectangular cross section

λ_g for the waveguide WR340 is calculated to be 148mm. Dimensions of the slots used in this model are 1mm (wide) by 2mm (depth) by 109mm (height). Slots are located such that slots on one waveguide are displaced from the other in order to achieve near homogeneous distribution of electric field within the NTPR.

Electric field distribution (E-Field) within a waveguide is calculated using COMSOL Finite Element Model (FEM). Following equation was solved in frequency domain by COMSOL to determine the electric field distribution in the waveguide and NTPR:

$$\nabla \times \mu_r^{-1}(\nabla \times \boldsymbol{E}) - K_0^2 \left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0}\right) \boldsymbol{E} = \boldsymbol{0} \qquad (3)$$

where μ_r-permeability of the medium, ε_0-permittivity of medium, $\boldsymbol{E}$-electric field vector, σ-density of medium and K_0 –wave number.

Walls of the wave guide and NTPR are assumed to be perfect conductors and the following boundary condition is applied:

$$n \times \boldsymbol{E} = 0 \qquad (4)$$

where n – normal vector to the walls.

Fig. 3(b)-(f) show the simulation results of the electric field distribution. Fig. 3(b) shows the electric field (E-Field) distribution of the waveguide in the x-z plane, across the middle of the waveguide in y direction. As can be seen the E-Field generates circular patterns along the waveguide and the slots are positioned where the E-Field maxima are located to get optimum value in the reactor. Positioning the slots is performed by varying the length of the waveguide (in practice by moving the plunger). In this modelling work, the length of each waveguide was found to be 510mm by trial and error. Figs. 3(c) to (e) show the E-Field in the reactor in three planes and field distributions are very non-uniform and make clusters across the planes as well as in the whole reactor. Finally, Fig. 3(f) shows a 3D representation of E-Field regions where the value of electric field is equal to 1V/m. These results clearly show that E-Field exhibits high degree of non-uniformity and hence it may be possible that a significant fraction of gas molecules may not undergo electron collisions and the follow up chemical reactions. Controlling non-uniformity can be achieved by tuning the following parameters: size of the slots (width and height), location and orientation of the slots, number of slots and vertical position of the waveguides with respect to the wall of the NTPR. Our next stage of wok will focus on fine tuning the above-mentioned parameters and find the best possible E-Field distribution to generate the microwave plasma.

IV. CONCLUSIONS

Microwave based non-thermal plasma reactor design is presented with finite element analysis. Slotted waveguide is an effective wave to transfer the MW energy into NTPR. There are a number of parameters to tune to get optimum electric field pattern within the NTPR. Initial results obtained from commercial MW oven plasma reactor suggest that MW alone can reduce NOx and SOx form the marine flue gas by 99% and 85% respectively.

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