# NITROGEN OXIDES REDUCTION IN A POROUS BURNER

**Shahrooz Afsharvahid**

**School of Mechanical Engineering**

**The University of Adelaide, South Australia 5005**

A Thesis submitted in fulfilment of the requirements for the Degree of

Doctor of Philosophy

**JULY 2016**

# STATEMENT OF ORIGINALITY

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# ACKNOWLEDGMENTS

I would like to express my special appreciation and thanks to my one and only supervisor, *Professor Bassam Dally*. He did a remarkable job as a supervisor and mentor. I am especially thankful to his continuous encouragement, support and more importantly for his true friendship which allowed me to successfully finish this work. His advice, ideas and brilliant instructions have helped my scientific and personal development and have guided me both in my research and career life.

I would like to also thank the School of Mechanical Engineering management team (especially Professor Anthony Zander) for supporting and funding my study, the workshop and laboratory staff (especially Mr. Graham Kelly) who supported my experimental work even at times where I found it hard to keep going.

I would also like to specially thank *Professor Peter Ashman* for the great help with the few publications I had and also his remarkable knowledge of the chemical kinetics.

I like to express my special gratitude to *Professor Farid Christo* for his valuable help with the numerical modelling techniques and encouragement guided me into great world of CFD.

I need also to appreciate the patience and support from my work colleagues and the management team in *FCT Combustion*. *Constantine Manias* and *David Retallack*, are a great inspiration in terms of hardworking and going to great length to achieve desirable results. *Russell Jackson* well taught me that there is nothing wrong with being a professional and at the same time fun to work with. I found him to be an expert in transforming impossible obstacles to exciting challenges.

Special thanks go to *Ms. Alison-Jane Hunter* for her kind assistance with proofreading my thesis. Her skills and talent was instrumental in greatly improving the readability of this thesis. I appreciate her phenomenal attention to details.

Words cannot express my gratitude to my loving and caring *mother*, inspiring *father*, my two brothers, *Shahraam* and *Shahrokh*, and my beautiful newly engaged sister, *Sara*. I will always remember the huge sacrifices they made for me to give me the best possible chance in life which made me who I am today.

I would also like to thank my life friend, *Parto* for the unconditional support, love and friendship, believing in me, standing by my side and giving me the strength unconditionally. I also have been blessed to have many trustworthy and loyal friends particularly *Keivan* and *Eyad* who were always around when I needed help, encouragement or support.

Last but not least, I would like to express my deep love and gratitude to my beloved son, *Kian*. Your bright little smile has given me the motivation to keep going, from the second you opened your eyes to this world. I would like to thank you for being such a bundle of joy and laughter in my life and I feel that I am the luckiest father of all times, being able to call you my son.

# ABSTRACT

Different aspects of porous burners have been studied in the past in terms of the bed material, design, heat transfer modes and flame characteristics. However, the application of porous burners to NOx reduction and the effect of the bed surface on the chemical reactions have not yet been explored. Hence, the objective of this study is to investigate the effect of the design and operating parameters on NOx reduction inside a porous burner.

To achieve this objective, a variety of flames, stabilised inside porous burners, were investigated experimentally, utilizing thermocouples, gas sampling and chromatography. Numerical tools were also used to understand the chemical pathways under different operating conditions better.

Premixed CNG-air and LPG-air flames at very low equivalence ratios were stabilised inside the porous bed. The relationship between the volumetric flow rate of the mixture and the minimum equivalence ratio was studied (experimentally and numerically) for equivalence ratios as low as $\varphi=0.35$ (equivalent to thermal power of 2kW). The maximum temperature observed to be consistent with super-adiabatic flame temperatures. The maximum measured $NO_X$ and CO mole fractions at the burner exit were found to be in the order of few PPMs.

The conversion of NOx was then assessed. A mixture of CNG-air doped with NO was introduced into the burner inlet and the effects of the operating parameters on NOx reduction were assessed. It was found that NOx reduction is a function of the equivalence ratio, total flow rate and NO mole fraction at the inlet. Higher flow rates led to an increase in the conversion rate at higher equivalence ratios, due to shorter residence times, and the greater need for more flame radicals in the flame.

The numerical study revealed that different chemical pathways dominate at different equivalence ratios, which led to the production of other intermediates and stable radicals. The study showed that the Total Fixed Nitrogen, TFN, reduction followed a similar trend to the NOx reduction for moderately fuel-rich conditions ($\varphi \leq 1.2$) and opposite trends for higher equivalence ratios. For $\varphi>1.2$, most of the NO is converted to N-containing species such as $N_2O$, $NH_3$ and HCN and not to $N_2$. Analysis of the chemical pathways showed that the formation of nitrogen-containing species under very fuel rich conditions is due to the increased importance of the HCNO path, as compared with the HNO path. The best TFN conversion efficiency, 65%, was found at $\varphi=1.1$.

Intermediate radicals have different rates of destruction and production on the porous bed surface, especially for mixtures close to stoichiometric conditions. Under these conditions, the conversion of $NO_X$ is strongly influenced by the concentration of H radicals. A collision probability of $\eta = 8\times10^{-4}$ was found to represent this radical loss effect and to help predict the destruction and production of intermediate terminals with a good level of accuracy.

This study also found that NOx reductions using porous burners are technically feasible and that the resulting CO in the exhaust, derived from the rich mixtures, can be burned outside the porous bed.

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# NOMENCLATURE

## i. Roman Symbols

| Symbol | Definition | Unit |
|---|---|---|
| $a$ | Surface Area Density | $m^{-1}$ |
| $A$ | Arrhenius pre-exponential factor | $s^{-1}$ |
| $A_{up}$ | Burner Cross Sectional Area | $M^2$ |
| $C_m$ | Measured $NO_x$ mole fraction | PPM |
| $Cp$ | Specific Heat Capacity | $kJ.K^{-1}$ |
| $c_{pg}$ | Specific heat of gaseous species | $kJ.kg^{-1}.K^{-1}$ |
| $C_r$ | Reference $NO_x$ mole fraction | PPM |
| $\Delta G_{ki}^{*}$ | The Gibbs free energy | $Kg.m^2.s^{-2}$ |
| $d_h$ | Hydraulic Diameter | M |
| $D_i$ | Molecular diffusivity of the $i^{th}$ species in Nitrogen | $m^2.s^{-1}$ |
| $d_p$ | Pore Diameter | M |
| $E$ | Arrhenius activation energy | $J.mol^{-1}$ |
| $EI_i$ | Emission Index | - |
| $EI_i$ | Emission Index | - |
| $F$ | Inertia coefficient | $m^{-1}$ |
| $f$ | Flame Location | m |
| $h_{\nu}$ | Convective heat transfer coefficient for the porous medium | $W.m^{-2}.K^{-1}$ |
| $K$ | Permeability | $m^2$ |
| $K$ | Specific permeability of the porous medium | $m^2/kg$ |
| $k_{cj}$ | Diffusion rate of radical species, $i$, to the burner surface | $s^{-1}$ |
| $k_{coll,i}$ | Surface collision rate constant for species $i$ | $s^{-1}$ |
| $k_{eff}$ | Effective rate of radical termination at the burner surface | $s^{-1}$ |
| $k_{g,e}$ | Effective thermal conductivity of the gas | $W.m^{-1}.K^{-1}$ |
| $k_j$ | First-order reaction rate constant for the $j^{th}$ reaction | $s^{-1}$ |
| $kk$ | Total number of gaseous species | - |
| $L$ | Bed length | m |

| | | |
|---|---|---|
| $m$ | Measured Oxygen concentration | Mole.m$^{-3}$ |
| $m''$ | Mass flow rate per unit area | kg.m$^{-2}$.s$^{-1}$ |
| $M_i$ | Molecular weight of the $i^{th}$ species | g.mol$^{-1}$ |
| $Nu_d$ | Nusselt number based on the average particle diameter of the packed bed | - |
| $P$ | Pressure | Pa |
| $Pe$ | Péclet number | - |
| $Pr$ | Prandtl number | - |
| $R$ | Universal gas constant, 8.314 | J/mol/K |
| $R$ | Reference Oxygen concentration | - |
| $Re$ | Reynolds number | - |
| $S_p$ | Laminar Flame Speed | m.s$^{-1}$ |
| $T$ | Temperature | K |
| $T_{amb}$ | Ambient temperature | K |
| $T_g$ | Gas temperature | K |
| $T_s$ | Solid temperature | K |
| $u_p$ | Superficial velocity (cross sectional velocity) | m.s$^{-1}$ |
| $V_{bed}$ | Cross-sectional mean velocity (Darcian velocity) | m.s$^{-1}$ |
| $V_p$ | Total Volume of Pebbles | m$^3$ |
| $V_{pm}$ | Volume of Porous Media | m$^3$ |
| $\overline{C}_i$ | Mean gas speed of species $i$ | m.s$^{-1}$ |

## ii. Greek Symbols

| Symbol | Definition | Unit |
|---|---|---|
| $\Phi$ | Equivalence ratio | - |
| $\gamma$ | Radical recombination efficiency = $k_{eff}$ / $k_{coll}$ | - |
| $\eta$ | Relative rate of radical termination = $k_{eff} / k_{ci}$ | - |
| $\mu$ | Dynamic viscosity | kg.s.m$^{-1}$ |
| $n$ | Arrhenius temperature coefficient | - |
| $\theta$ | Burner surface-to-volume ratio (6400m$^{-1}$, for this burner) | m$^{-1}$ |
| $\rho$ | Gas density | Kg.m$^{-3}$ |
| $\sigma$ | Stefan-Boltzmann constant | W.m.K$^{-4}$ |
| $\overline{\sigma}$ | Average Reaction Rate | Mol.s$^{-1}$ |
| Δ | Packed Bed Sphere Diameter | m |
| E | Porosity | - |
| Λ | Coefficient of Thermal Conductivity | - |
| $\nu$ | Kinematic viscosity | m$^{2}$.s$^{-1}$ |
| σ(x) | Net Reaction Rate | Mol/cm$^{3}$s |
| $\tau_{eff}$ | Effective Residence Time | s |
| $\overline{\Phi}$ | GER, Global equivalence ratio | - |

## iii. Acronyms and Abbreviations

| Acronym | Definition |
|---|---|
| CNG | Compressed Natural Gas |
| FLOX | Flameless Oxidation |
| HVR | High Velocity Regime |
| LPG | Liquefied Petroleum Gas |
| LVD | Low Velocity Detonation |
| LVR | Low Velocity Regime |
| MILD | Moderate or Intense Low oxygen Dilution |
| ND | Normal Detonation |
| NOx | Nitrogen Oxides |
| PB | Porous Burner |
| PBM | Porous Burner Model |
| PPB | Part Per Billion |
| PPM | Part Per Million |
| PRB | Porous Radiant Burner |
| RCR | Rapid Combustion Regime |
| SCW | Super-adiabatic Combustion Wave |
| SVR | Sound Velocity Regime |
| TFN | Total Fixed Nitrogen |