Non-Thermal Plasma Approach To Simultaneous Removal of NOx & Particulate Matter

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Delphi Energy & Chassis Systems
Delphi System Approach
Project Structure
Modeling
Reactor Design
Power Requirements / Supply
Catalyst & Mechanisms
Particulate Filter Regeneration
Summary / Timing
Non-Thermal Plasma Exhaust Aftertreatment NTP System Diagram

High Efficient Generator

DI Diesel Engine

NTP Controller

High Voltage / High Frequency Power

NTP Reactor

Particulate Filter

Catalytic Converter

\( \text{HC, NO, N}_2, \text{O}_2, \text{H}_2\text{O, CO, CO}_2 \)

\( \text{NO}_2, \text{Metastables, Partially Oxidized HC, O}_2, \text{H}_2\text{O, N}_2, \text{CO, CO}_2 \)

\( \text{N}_2, \text{H}_2\text{O, CO}_2, \text{O}_2 \)
Team Structure

- Reactor Design, Modeling, and Testing
  - D-E Flint
  - PNNL

- Power Supply Development & Vehicle Integration
  - D-E Flint
  - D-D Kokomo
  - PNNL

- Application, Benchmarking & Competitive Analysis
  - D-E Luxembourg

- Catalyst Developments, Mechanistic Studies & Chemical Analysis
  - Delphi R&D
  - ASEC
  - D-E Flint
  - PNNL
  - Northwestern University

- Particulate Trap Regeneration & Testing
  - D-E Flint
  - ASEC

Delphi Energy & Chassis Systems
Reactors Modeling

Purpose

- Develop predictive performance and plasma chemistry tools for an NTP reactor
  - Insights for reactor optimization and energy efficiency
  - Qualitative screening of reactor design concepts

- Develop working model to guide reactor design
  - Power requirements and operating parameters
  - Geometry and properties
    » Gap width and thickness, barrier material and thickness, etc
    » Voltage requirements, frequency, space velocity

- Insights on or resolution of operational issues

- Diagnosis and interpretation of experiments
Reactor Modeling
Discharge Model

- Ionization Coefficients
- Attachment coefficients
- Electron mobilities
- Weighted X-sections

Discharge Plasma Model

- Cross section data for electron impact
- Gas composition
- E/n values

NTP Reactor data - Geometry and materials

- Electric filed in gap
- Current in gap
- Power in plasma

Electrical Performance Model (I)

- Electron impact rates
- Reactant production (O, H, OH, etc)

Chemical Kinetics Code

- Nitrogen oxides and acids
- Hydrocarbons
- Oxidation products

Electrical Model (II)
Discharge plasma model – ELENDIF

- Calculates electron energy distribution and rate parameters for electron impact production of ions and reactants
- Determines electron transport parameters: ionization, attachment, drift velocity or mobility

Electrical performance models

- Relates time-dependent electric currents, electron and ion fluxes, electric field, and power deposited in plasma to geometry, materials, and time-dependent driving voltage
- Calculates power and reactant production rates over space and cycle
- Versions for detailed time-dependence model and “ultimate performance” model for hard electrical driving

Chemical kinetics code – CHEMKIN

- Calculation of subsequent NOx chemistry from radical formation
Reactors Design

- **Reactor Can**
  - Weight: 3.3kg
  - Length: 121mm
  - Width: 120mm
  - Height: 110mm

- **Reactor Brick**
  - Length: 165mm
  - Width: 137mm
  - Height: 83mm
Fuel Use as a function of Additional Electrical Load
(from Luxembourg data on Opel Vectra 2.0 Dti)

Constant Additional Load (W)

Increase in Fuel Consumption (%)
Power used vs. fuel economy penalty
- Target
  » 2-3% fuel economy penalty

How much energy can we use??
- Calculated (based on emission data)
- European driving cycle testing (Opel vectra w/ constant electrical loads)
- Customer input (1kW=0.8l/100km on cycle)
  » 300 W acceptable on cycle

Target power consumption
- 300 W average on driving cycle
- 1000 W peak
Power Supply
Current Configuration

3kW 42V Alternator

1kW 42V/14V DC/DC Converter

12V Battery

12V Loads

High Power Inverter

Step-up Transformer

NTP Reactor

System Controller
Vehicle Integration
Future Direction

- Reduce power consumption
  - Additional Hydrocarbons
    » Balance between electrical and fuel use for total fuel penalty
    » EMS Solution (EO emissions)
    » Post injection methods
    » Supplemental HC injection
  - Optimize Power Delivery System
  - Optimize Reactor Design with respect to power efficiency

- Reduce cost
  - Lower power design (300 W average, 1000 W peak)

- Reduce size
  - Integrate components

- Meet emission and electrical targets
Effect Of HC Injection - Idle

Effect of HC(propene) Injection @ Idle on NO->NO2 Conversion
2.0L Opel diesel exhaust, Slip Stream - 1 cell reactor, 1mm gap, 1.2M/hr S.V., crown 5000 w/ sinusiod input, 11L/min flow, 5000Hz, reactor inlet temp 150C, 160ppm NO, 180ppm NOx feedstream
System NOx conversion has increased through time

Similar results with exhaust from two vehicles with low HC levels
Regeneration: The Challenge

- Particulate mass captured in the DPF is removed by “regenerating” the filter. Regeneration is accomplished by combusting the carbon and HC mass captured in the filter.

- Natural soot ignition temperature: 550°C - 600°C. This temperature range greatly exceeds the typical diesel exhaust temperature under most driving conditions.

- Combustion of the trapped carbon and HC can create a large exotherm which can melt or damage the trap; particularly at low engine flow.

Consistent, reliable regeneration of the trap is the biggest technical challenge to the DPF system.

Regeneration System Types

- Active Regeneration Systems
  » Heat the exhaust gases or filter above the particulate ignition temperature
  » Examples: burners, electrical heat, microwave

- Passive Regeneration Systems
  » Lower the particulate ignition temperature either by adding a catalyst to the trap or fuel, or by forming a stronger oxidizing agent in the exhaust gases (NO\textsubscript{2}).
  » Competing technologies:
    - Fuel additives
    - Catalyzed traps
    - NO\textsubscript{2} from oxidation catalyst
    - NO\textsubscript{2} from Non-Thermal Plasma
Why a NTP Reactor Instead of CRT?

- Generates NO\textsubscript{2} below 250\degree C.; in addition, NTP generates other species which may also contribute to the oxidation of soot at low temperatures.
- NTP performance not affected by sulfur in fuel.
- Generates appropriate NO\textsubscript{2} levels needed for a reliable filter regeneration.
- NO to NO\textsubscript{2} conversion efficiency higher than 70\%
At 150°C (dry feed), N₂ and CO₂ grow in together, showing HC selective catalytic reduction of NO₂ to N₂.

NOx adsorption saturates much more slowly (> 8 hours).
With water present, NOx adsorption saturates rapidly.

Catalysis forming N₂ and CO₂ still proceeds as when dry.

NOx adsorption and reaction to form N2 are decoupled.
MAIN CATALYST FINDINGS

Similar time dependence of \( \text{N}_2 \) and \( \text{CO}_2 \) formation clearly demonstrate hydrocarbon selective catalytic reduction (HC-SCR) of \( \text{NO}_2 \) to form \( \text{N}_2 \) at 150°C.

The same quantitative relationship between \( \text{N}_2 \) and \( \text{CO}_2 \) is observed between 150°C and 200°C.

Very different time dependence of \( \text{NO}_2 \) adsorption and catalytic reaction shows they are decoupled and may occur at different sites.

Dominant product of \( \text{NO}_2 \) adsorption is NO.

At 200°C for a space velocity of 12,600 h\(^{-1}\) the conversion of \( \text{NO}_2 \) to \( \text{N}_2 \) is 50%.

Optimization of the catalyst should lead to higher activities.
Summary

Key NTP Benefits

- Low temperature operation
- Not affected by sulfur
- Flexible options:
  - NOx reduction
  - Particulate matter reduction
  - Both
- Applicable to the full range of diesel vehicles and direct injection gasoline vehicles.
- Potential of combining de-pollution and noise reduction.

The NTP exhaust aftertreatment system has the potential to make a difference; therefore the team is aggressively pursuing this technology in order to turn it into a commerciable product and be first in the market.

Timing

- Target Production 2004 CY (2005 MY)
- Samples available end of 2000 - beginning 2001