Interacting-Sprays Injection

From Liquid Rocket Engine to Diesel Engine

An Original Concept Proposed

By

Bruce Chehroudi, PhD

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www.AdvTechConsultants.com
Interacting-Sprays Injection: An Innovative Fuel Injector Strategy

- Idea was originally proposed and named (as “Interacting Sprays Injection”) by B. Chehroudi, PhD.
- Inspired by impinging jets injector design used in F-1 Rocket engine.

- Impinging jets offers an additional mechanism to standard aerodynamic breakup of the liquid core
  - Hence, no need to use very high injection pressures for atomization, because the impinging-jets process (if impingement point is optimized) assists the liquid core breakup.

- Initial impingement angle and injector holes separation values were guided by rocket applications and knowledge of intact core of full-cone diesel sprays.
- Injector design flexibility due to additional parameters that can be varied for optimum injection and mixture preparation.
- Proof-of-concept was demonstrated with two independent injectors (see original publication in the next slide). However, in application, what Chehroudi et al. had in mind was that a single injector unit to achieve the objectives in diesel engines (see some works that were published after Chehroudi’s original research briefed in upcoming slides).
- Flexible features to produce not only "pilot and split injections," but additional injection strategies not possible with other approaches for emission reduction, performance, and efficiency improvements.
- The original work and first SAE publication by Chehroudi et al. predates all applications of interacting or impinging sprays in diesel engines.
- Applications of this injection system has been shown for early injection homogenous operation in diesel engines.
Interacting-Sprays Injection: Original Publication

This is the first publication in literature, describing application of Interacting-Sprays/Jets (or Impinging-Sprays/Jets) in a research diesel engine.

A Novel Approach for Simultaneous NOx and Smoke Reduction: Interacting-Sprays Injection

SAE Paper 961678
1996-08-01

https://www.sae.org/publications/technical-papers/content/961678/
Interacting-Sprays Injection Strategy

INTERACTING-SPRAYS INJECTION: A NEW CONCEPT FOR NO\textsubscript{x} AND SMOKE REDUCTION IN DIESEL ENGINES

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In the past decade many in-cylinder injection approaches have been proposed for simultaneous reduction of NO\textsubscript{x} and smoke in diesel engines, with various degrees of success in operation. In this article, some results from a novel and promising technique referred to as the interacting-sprays injection concept is presented. A single-cylinder compression-ignition two-stroke research engine with optically accessible head mounted on a high-speed CFR (cooperative fuel research) engine crankcase is used to investigate the combustion and emission characteristics of this injection system. The interacting-sprays injection system produces two separate, independently controlled liquid fuel spray injections with a good degree of adjustability with regard to their fuel quantities and injection timings. The impingement schedule of the two sprays on each other at the right time and place inside the combustion chamber is the key to the success of the interacting-sprays injection system. Results are presented that show the effects of the varied injection system characteristics on the combustion and exhaust emissions (NO\textsubscript{x} and smoke). The effects of the injection timing and time separation between the first and second injections of the interacting-sprays injection system are explored. Conditions are identified for which a favorable influence on both smoke and NO\textsubscript{x} production is observed. A promising and new injection system and strategy are therefore proposed as a result of the data acquired in this study.
Engine head design for laser sheet entry into the combustion chamber for Exciplex flow visualization enabling simultaneous visualization of both the liquid and vapor phases.
DETAILS OF THE ELONGATED CYLINDER-PISTON ASSEMBLY SHOWING THE POSITION OF THE WINDOWS
Visualization 2-Stroke Engine Design (1989)

B. Chehroudi’s visualization engine at Princeton University, 1989
Interacting-Sprays Injection: Injector Information

Injection System Specification

- Fuel Injector Nozzles:
  - Stanadyne slim-tip pencil nozzles
  - Single spray orifice drilled at 66 degrees to nozzle axis
    - First: One hole at 0.43mm (0.017in) dia.  
      L/D ratio: 1.53
    - Second: One hole at 0.38mm (0.015in) dia.  
      L/D ratio: 1.73
  - Measured spray impingement angle from images: 12° to 14°
  - Valve operating pressure: 20.8 MPa (2,800 psig)
- Injection timing:
  - First: Continuously variable w.r.t. crankangle position
  - Second: Continuously variable w.r.t. crankangle position
- Fuel pumps; Ambac APE
- Cam profiles: Ambac #1 basic metric
- Fuel pump plunger diameter:
  - First: 8.0mm
  - Second: 5.0mm
- Fuel pump delivery valve retraction volumes:
  - First: 50 mm³
  - Second: 50 mm³
- Injection line:
  - Internal diameter: 2mm (0.079in)
  - Length:
Interacting-Sprays Injection: Injectors Used

Hall Effect Sensors
Interacting-Sprays Injection: Test Setup

General Arrangement

Laser Power Supply

Main Fuel Pump
Oldham Coupling
TMB Timing Device
Pilot Fuel Pump
Candy Differential

 CFR Crankcase

Dynamometer

Shaft Encoder

Elongated Piston (in cylinder)

Exhaust Manifold

Camera

Head

Beatriz Chehroudi, PhD
Interacting-Sprays Injection: Intake System for Exciplex Visualization

![Diagram of the nitrogen/air intake system](image)

**Figure 4.** Schematic of the nitrogen/air intake system.

SETUP FOR LASER INDUCED FLUORESCENCE (EXCIPLEX) MEASUREMENTS USING NITROGEN INSTEAD OF THE AIR

B. Chehroudi, PhD
Interacting-Sprays Injection: Emission Measurements

ENGINE EMISSION MEASUREMENT SETUP
Brief Background: Diesel Engine Spray and Heat Release Rate

- SPRAY IS CONVECTED IN THE AIR SWIRL DIRECTION
- A CONTINUOUS SPECTRUM OF AIR/FUEL RATIOS EXISTS

BACKGROUND:
I. IGNITION DELAY PERIOD
II. PREMIXED COMBUSTION PHASE
III. MIXING-CONTROLLED COMBUSTION
Figure shows injection of two jets from the two injectors. The second injection begins at about 4° BTDC. The spray cores impinge at about 2° BTDC. After about 2° ATDC, only the second injector continues injection into the combustion chamber.
Interacting-Sprays Injection: NOx vs. Smoke Tradeoff

The NOx-Smoke trade-off curves for the four injection strategies shown. BOI stands for the beginning of the injection.

Measurement uncertainty:
NOx = +/- 1.8% of the reported data.
BSN= +/- 3.45% of the reported data.
Results for all the interacting-sprays and single-injection strategies plotted as functions of crank angle degrees. For horizontal axis, zero and negative numbers are at TDC and before TDC (i.e., BTDC), respectively.

Injection scheduling:
- (a) single injection
- (b) coincident split
- (c) second injection ends at ignition
- (d) 12° separation

Measurement uncertainty:
- NOx = +/- 1.8% of the reported data.
- BSN = +/- 3.45% of the reported data.

With respect to Conventional Single Injection fuel injection strategy:
- Simultaneous injection leads to reduction in smoke
- Injection with time separation leads to reduction in NOx
- Therefore, strategies can be envisioned for simultaneous reduction in smoke and NOx.
Research work reported by others following the research conducted by Chehroudi et al. Chehroudi’s work predates all such applications in diesel engines.
INTERACTING-SPRAYS INJECTION SYSTEM: Work by Others

Research work reported by others following the research conducted by Chehroudi et al. Chehroudi’s work predates all such applications in diesel engines.

Combustion and Emission Characteristics of Premixed Lean Diesel Combustion Engine

Keiichi Nakagome, Naoki Shimazaki, and Keiichi Niimura
New ACE Institute Co., Ltd.

Shinji Kobayashi
Japan Automobile Research Institute, Inc.

Approaches to Solve Problems of the Premixed Lean Diesel Combustion

Hisashi Akagawa, Takeshi Miyamoto, Akira Harada, Satoru Sasaki, Naoki Shimazaki, Takeshi Hashizume and Kinji Tsujimura
New ACE Institute Co., Ltd.

Inter-spray Impingement of Two Diesel Sprays

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ILASS/ICLASS CONFERENCE, PASADENA, CALIFORNIA, 2000

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Communication with Prof. Masataka Arai, reminding that Chehroudi’s research work on Interacting-sprays (or impinging sprays) injection was the first application of such concept in a research diesel engine.

Acknowledgement of this fact by Prof. Arai can be seen in his response.
INTERACTING-SPRAYS INJECTION SYSTEM: Work by Others

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Premixed compression-ignition (PCI)

Trial of New Concept Diesel Combustion System - Premixed Compression-Ignited Combustion -
Yoshinori Iwabuchi, Kenji Kawai, Takeshi Shoji, and Yoshinaka Takeda
Mitsubishi Motors Corporation

<table>
<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>PCI Combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression Ratio</td>
<td>18.5</td>
<td>12.0</td>
</tr>
<tr>
<td>Combustion Chamber</td>
<td>High dish</td>
<td>110 Bowl type</td>
</tr>
<tr>
<td>Injection Nozzle</td>
<td>( \Phi 0.21 \times 5) - 157°</td>
<td>( \Phi 0.21 \times 5) - 80°</td>
</tr>
<tr>
<td>Injection Pressure</td>
<td>80MPa</td>
<td>–</td>
</tr>
</tbody>
</table>

Premixed compression-ignition (PCI)

**Figure 8.** Spray Characteristics of Impinged-Spray Nozzle (1 set of impinged holes)

**Figure 12.** Configuration of Impinged-Spray Nozzle with Engine Tests (5 sets of impinged holes)

**Spray Characteristics of Impinged-Spray Nozzle**

To achieve a spray with not only low penetration and high dispersion, but also good atomization and a short injection period, it is necessary to maintain a high injection rate. With a view to creating a spray with these characteristics, the sprays formed with various spray-to-spray impingement angles were observed (Fig. 8). Nozzles which have one set of impinged holes and high pressure vessel were used for spray observation.
INTERACTING-SPRAYS INJECTION SYSTEM: Work by Others

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INTERACTING-SPRAYS INJECTION SYSTEM: Work by Others

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1999-01-0185

Trial of New Concept Diesel Combustion System
- Premixed Compression-Ignited Combustion -

Yoshinori Iwabuchi, Kenji Kawal, Takeshi Sjoji, and Yoshinaka Takeda
Mitsubishi Motors Corporation

ABSTRACT

A premixed compression-ignited (PCI) combustion system, which realizes lean combustion with high efficiency and low emissions, was investigated and its effects and problems were ascertained. With PCI combustion, fuel was injected early on the compression stroke and a premixed lean mixture was formed over a long mixing period. The test engine was operated with self-ignition of this premixed lean mixture. From the results of combustion observation and numerical simulation, a need to prevent the fuel spray from adhering to the cylinder liner and combustion-chamber wall was identified. Consequently, an impinged-spray nozzle with low penetration was made and tested. As a result, an extremely low nitrogen-oxide (NOx) emission level was realized but fuel efficiency was detracted slightly. Also, the engine operating range possible with PCI combustion was found to be limited to partial-load conditions and PCI combustion was found to cause an increase in hydrocarbon (HC) emission. Since it offers ideal combustion characteristics with a high degree of constant volume of heat release, however, PCI combustion potentially represents a more efficient, cleaner combustion (ultra-low NOx and low smoke) than those of conventional diesel engines.

Premixed compression-ignition (PCI)

CONCLUSIONS

With regard to PCI combustion with early direct injection, combustion observation and numerical simulation were performed, improvements in spray characteristics were achieved, and tests were performed with a view to reducing fuel consumption, expanding the operating range, and reducing HC emission. The study yielded the following conclusions:

(1) When early direct injection is performed with a conventional hole nozzle, the spray's penetration is significant and fuel adheres to the combustion-chamber wall. NOx emission is reduced, but fuel consumption and HC emission increases. Thus, a spray with low penetration and wide dispersion is required.

(2) PCI combustion is a form of lean combustion that is not accompanied with a luminous flame, and it takes place throughout the combustion chamber.

(3) An impinged-spray nozzle realizes the low-penetration, high-dispersion, and high injection rate required with early direct injection, and it produces a spray that is suitable for PCI combustion.

(4) Compared with PCI combustion using a hole nozzle, PCI combustion using an impinged-spray nozzle offers significant reductions in fuel consumption and smoke emission, and it realizes combustion with ultra-low NOx and low smoke emissions. However, fuel consumption is slightly higher than that of conventional diesel combustion.

(5) Supercharging enables expansion of the operating range with PCI combustion possible.

(6) An oxidation catalyst can be used to reduce HC emission comparable with that of conventional diesel combustion. With low operating load, however, the effect of an oxidation catalyst is insufficient and another means of HC reduction is necessary.

Although PCI combustion realizes ultra-low NOx emission and low smoke emission, it is slightly inferior to conventional combustion in terms of fuel consumption. Provided some reliable means of controlling ignition is found and optimizing the compression ratio is carried out in terms of fuel consumption, the PCI combustion system potentially represents a new combustion system that is both clean and highly efficient.

B. Chehroudi, PhD
INTERACTING-SPRAYS INJECTION SYSTEM: Work by Others

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Figure 13. Fuel Spray Configuration of Impinged-Spray Nozzle (*N₂, 0.4MPa*)

*1: Same atmospheric density as that in the cylinder at 50° BTDC in engine test

Figure 14. Penetration of Impinged-Spray Nozzle

Figure 12. Configuration of Impinged-Spray Nozzle with Engine Tests (5 sets of impinged holes)

1999-01-0185

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Research work reported by others following the research conducted by Chehroudi et al.
Chehroudi’s work predates all such applications in diesel engines

• Sponsored by SCANIA
• Used interacting or impinging sprays
• Early injection for HCCI
• Published in 2007

https://pdfs.semanticscholar.org/ec64/31cc0e8c35e221b44344b3bfec3bf7ea7cf9.pdf
Dr. Chehroudi met Prof. Phillip Hill at the 1996 SAE Future Transportation Technology Conference & Exposition, Powerplants of the Future-SP-1187, held in Vancouver, B. C., Canada, where his Interacting-Sprays injection was presented.
INTERACTING-SPRAYS INJECTION SYSTEM
A Concept Brought from Liquid Rocket Injection to Diesel Engine
by
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Supercritical Rocket Like-Impinging Jets
Chehroudi et al.
The End

An Original Fuel Injection Concept Brought From Liquid Rocket Engine to Diesel Engine
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