

Study of Jet Behavior and Mixture Formation Processes in Hydrogen Engines

Ken Ayukawa ¹⁾ Akichika Yamaguchi ¹⁾ Seiya Nishimura ¹⁾ Sasaki Satoru ¹⁾

Masanori Goto ¹⁾ Kazufumi Serizawa ¹⁾

¹⁾ DENSO CORPORATION

1-1, Showacho, Kariya, Aichi, 448-8861, Japan (E-mail: ken.ayukawa.j3u@jp.denso.com)

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Hydrogen engines are a promising option for achieving carbon neutrality in heavy-duty applications. However, homogeneous mixture formation remains a challenge in swirl-dominated combustion systems because it strongly affects NO_x emissions. In this study, CFD simulations and single-cylinder engine experiments were conducted to clarify the mixture formation mechanism and injection requirements for a heavy-duty hydrogen direct-injection engine. CFD-derived equivalence-ratio distributions were used to estimate NO_x emissions.

Figure 1 compares measured NO_x emissions with values estimated from CFD-derived equivalence-ratio distributions. The proposed method successfully reproduced the EOI-NO_x relationship under different engine speeds and loads. Both measured and predicted results exhibited a common inflection point around EOI = 80~90 BTDC, indicating that NO_x formation is governed by local equivalence-ratio distributions rather than the mean equivalence ratio alone.

To clarify the origin of this common EOI sensitivity, the mixture formation process was analyzed using the CFD results shown in Figure 2. Figures 2 (a) - (d) show cylinder volume, the mass fraction of ultra-lean mixture ($\Phi = 0\sim 0.1$), turbulent intensity, and predicted NO_x, respectively. The results revealed that vortex-breakdown-induced turbulence occurs during the late compression stroke. When injection is completed before this event, fuel transport is nearly finished and the generated turbulence effectively promotes hydrogen-air mixing, suppressing locally rich regions and NO_x formation. In contrast, when injection continues into the vortex-breakdown period, unmixed air remains in the cylinder and NO_x increases rapidly.

These findings indicate that mixture homogenization is governed by the interaction between fuel transport and turbulent diffusion rather than mixing time alone. For the present engine configuration, completing injection before approximately 90 BTDC was effective for achieving homogeneous mixture formation and low NO_x emissions. Furthermore, assuming a typical heavy-duty diesel engine IVC timing of 150 BTDC, the optimal injection duration was found to be approximately 60 CA. An injector capable of delivering the required fuel quantity within this duration, together with flexible fuel-pressure control, is desirable for maintaining the target injection duration over a wide operating range.

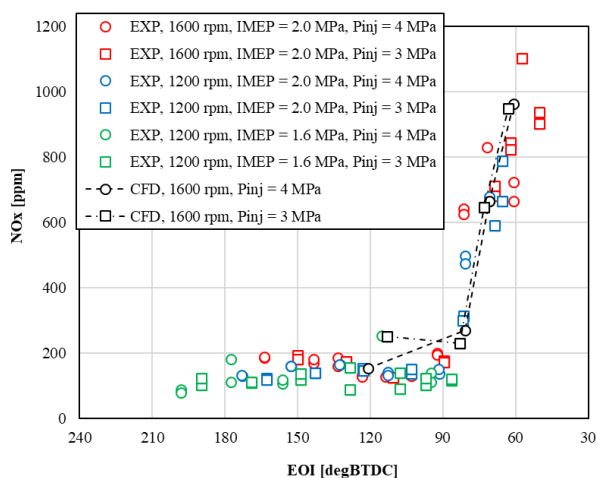


Figure 1. Effect of EOI on NO_x emissions

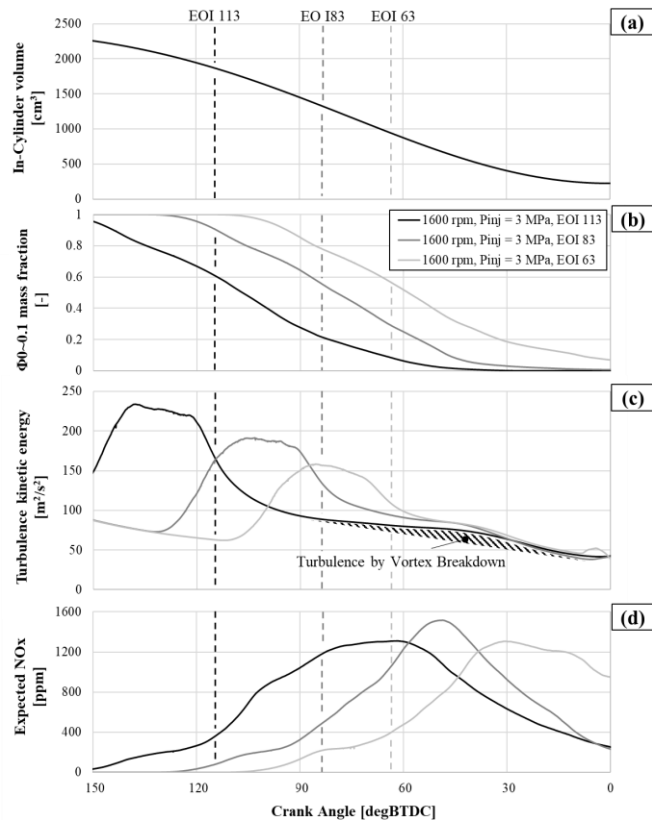


Figure 2. Mechanism of turbulence effect on NO_x formation